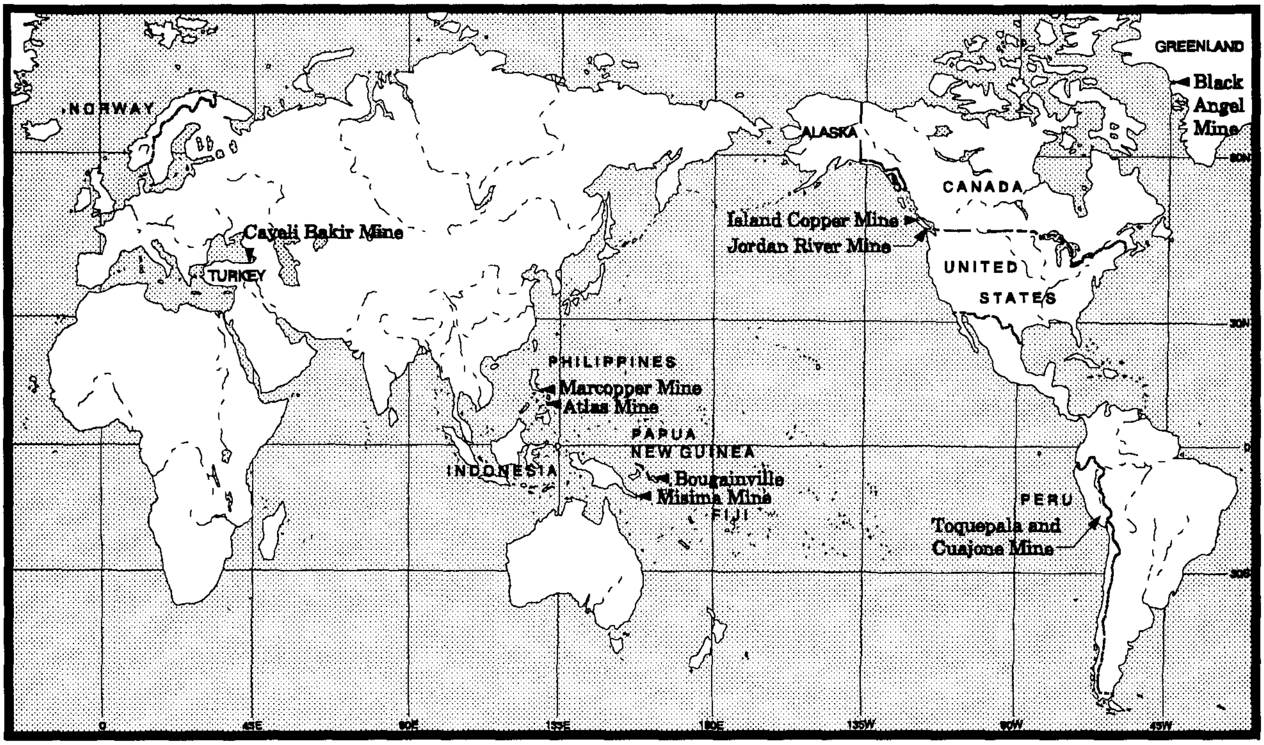
CASE STUDIES OF SUBMARINE TAILINGS DISPOSAL:

VOLUME II - WORLDWIDE CASE HISTORIES AND SCREENING CRITERIA



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CASE STUDIES OF SUBMARINE TAILINGS DISPOSAL: VOLUME II - FURTHER CASE HISTORIES AND SCREENING CRITERIA

A Report Resulting from a Cooperative Agreement with the University of British Columbia

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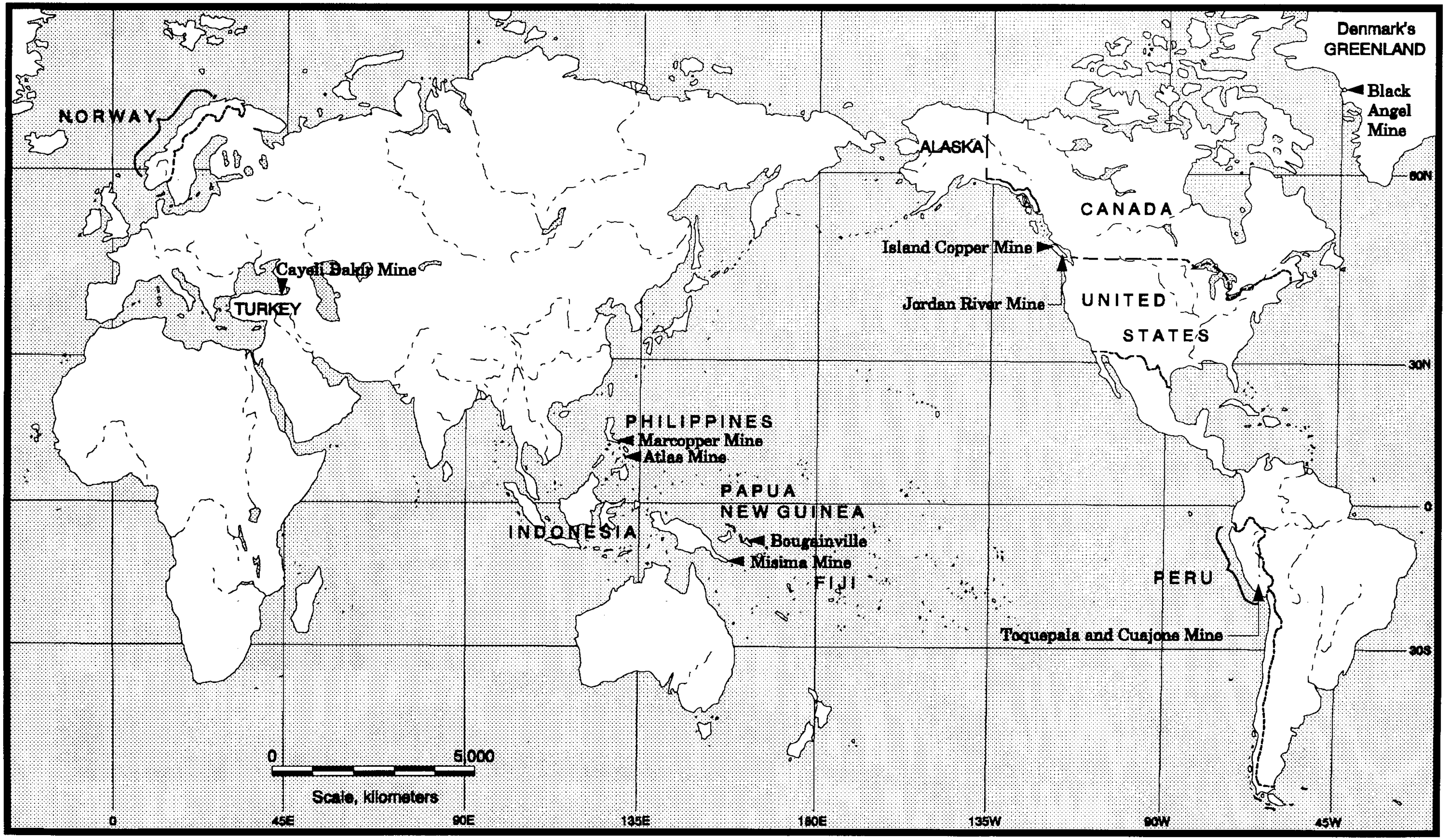

Frontispiece: World Map Showing All Sites.

Preface and Acknowledgements

In each case-history we have followed the general descriptive sequence set in Volume I, i.e. the mine, the orebody and milling process, and finally the environmental impact . However, it should be noted that the amount and content of documentation publicly available, or available to us, for the various cases is not consistent.

In some cases we have had access to industry documents. For these, we have sought approval from the mining company concerned to use the information contained, to reference the document, and in some cases to quote sections. We very much appreciate co-operation in this form from Placer Pacific Ltd., and BHP-Utah Ltd.

We greatly appreciate assistance from T.Pedersen over Section 1.2 Acid Generation in Discharged Tailings. Also, assistance from K. Ellis in development and management of this Volume. She is the co-author with D.Ellis of Section 1.4, Very Deep STD, and the translator of Section 1.4.3.

We also appreciate permission from BHP-Utah Ltd. to reprint a review of the geochemistry of sulphate-reducing bacteria (SRB). This was originally part of a larger report to Island Copper Mine by the author (K.A. Perry).

Formal external reviewers have been generous in their time. We thank them, particularly W.Klein, W.Kuit, G.Asmund, and G. Murray. They have all carefully read the original manuscript, and their helpful comments have made us recheck our statements, and rephrase them in many places.

Photographs are by the authors. Figures have been drafted or redrafted by John Ellis.

Conversions Constants

foot	x	0.3048	=	meters
yard	x	0.9144	=	meters
fathom	x	1.8288	=	meters
cubic foot	x	0.02831	=	cubic meters
ton (short)			=	2,000 lbs
	x	907.18	=	kilograms
	x	0.90718	=	tonnes (metric)
lbs/ton	x	500	=	milligrams/kilogram or ppm

CASE STUDIES OF SUBMARINE TAILINGS DISPOSAL:
VOLUME II - FURTHER CASE HISTORIES; SCREENING CRITERIA

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Abstract

Volume II of this two-part series on Submarine Tailings Disposal (STD) as a tailings management option for coastal and island mines contains descriptions of lesser known case histories.

The Misima gold mine (Papua New Guinea) and the Black Angel lead-zinc mine (Greenland) are described in some detail as the best documented cases. Atlas copper mine (The Philippines) is less fully described due to relative lack of documentation. The Misima and Atlas STD systems are working to their design criteria. At Black Angel the system adopted did not prevent contamination for a number of reasons, which are now understood.

Two cases are described where STD is being developed. They are the Cayeli Bakir copper mine (Turkey), and the Toquepala and Cuajone mines (Peru). There is excellent documentation available for both cases.

Three case histories are described where tailings have reached the sea either through beach or river discharge. In one case the STD option has been explored (Marcopper Mine, The Philippines). In the others we explore in hindsight whether STD might have been a viable alternative using the Screening Criteria that this Volume develops - see below. The mines are Bougainville Copper Mine in Papua New Guinea, and Jordan River Mine (Canada). There is potential for STD at all three sites.

Finally, the Volume presents Screening Criteria for appraising STD, based on the experience in design, operation and environmental impact reviewed in the case histories.

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Dr. Poling is Professor of Mineral Process Engineering at the University of British Columbia. He has acted as an environmental and process advisor to BHP's Island Copper Mine since 1971 and for Jordan River Mine and the Quartz Hill Mine proposal. At present he coordinates the Island Copper Mine Environmental Advisory Committee dealing with submarine tailing disposal, waste rock disposal and closure planning. He has authored several articles on submarine disposal and serves on several joint industry-government-academic committees dealing with mine environmental protection and land reclamation.

C.A. Pelletier, B.Sc.

Mr. Pelletier, President of Rescan Consultants Inc., has an extensive background in the chemical/metallurgical/environmental aspects of precious metals, base metals, potash and coal mining developments. His experience in submarine tailings disposal is very extensive. Environmental auditing, risk analysis and hazardous site investigations are also areas of his particular expertise. Mr. Pelletier has over twenty years of experience in industry and consulting which qualifies him to provide technical advice and guidance for resource development projects on an international basis.

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EXECUTIVE SUMMARY

Volume II of this two-part series on Submarine Tailings Disposal (STD) as a tailings management option for coastal and island mines contains descriptions of lesser known case histories.

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Finally, the Volume presents Screening Criteria for appraising STD, based on the experience in design, operation and environmental impact reviewed in the case histories. For those designing or appraising new STD systems or upgrading existing tailings disposal systems to STD, we stress the need for contemporary information on tailings management, on metals release by milling processes and from tailings, and on procedures for environmental impact assessment.

The seven Screening Criteria are: (1) location within distance of the coast for cost-effective onland tailings transport, (2) bathymetry with suitable slope to develop a tailings density current to an adequately-sized final deposition site, (3) availability of a suitable coastal outfall site, (4) minimal potential for bioactivation of contaminants, (5) minimal potential for suspension or re-suspension of tailings fines, (6) minimal (preferably only temporary) losses of other resources, and (7) socio-economic acceptance.

A step-wise procedure for using the Screening Criteria is presented. We hope this will be useful for industry, regulatory agencies and others with interests in the management of tailings from coastal and island mines.

1.0 INTRODUCTION

1.1 General Introduction

Volume II of this two-volume report on Submarine Tailings Disposal (STD) includes cases less well documented than those described in Volume 1 (Poling and Ellis, 1993). Volume II also includes cases where STD was an option which was not taken, and describes how, in hindsight, STD might have been used.

Large scale tailings disposal presents many engineering challenges, and there is considerable potential for environmental problems. Two of our cases, Black Angel and Jordan River, show how the chosen STD did not work effectively. At Black Angel this was through insufficient understanding of discharge chemistry at the site. At Jordan River, the problems developed through inadequate design for a wave-swept, high energy coastline and from cost-cutting construction. These cases are valuable now as they show how STD design options need to be established for specific mining and environmental parameters.

This Volume concludes with a chapter developing Screening Criteria for STD. By this, we mean criteria by which STD can be appraised as a tailings disposal option: either at new mines, or at sites where existing mines must reduce their environmental impact. The Criteria are based on the experience and knowledge obtained through the case histories documented in Volumes I and II.

Development and presentation of Screening Criteria is the purpose of this compilation of experience with STD. It is the intent that these Criteria will allow objective appraisal of STD, and will help in decision-making whether or not to adopt STD at specific sites.

Mine locations are shown in the Frontispiece. Appendix 1 provides photographs of an operating STD outfall at Island Copper Mine, Canada.

1.2 Acid Generation in Discharged Tailings

Mine tailings can be an environmentally deleterious waste due to the potential to produce acids by chemical or bacterial action. The acids can then leach otherwise chemically inert trace toxins, and render them biologically available. There is an enormous literature on the topic which we do not attempt to summarize. Essentially the acidity is derived from the exposure of sulphide minerals to air and water. The process is greatly accelerated by bacterial action.

The acid-generating process can be buffered chemically by alkaline rocks, and reversed by sulphate-reducing bacteria (SRB). Metal sulphides are thereby precipitated and immobilized, particularly in permeable rock onland or sediment sinks underwater. SRB are found in greatest numbers in anoxic sediments, but some can function in anoxic microenvironments, or low oxygen conditions, near the surface of sediments flushed by oxygenated water. Anoxic water overlying beds of subaqueous tailings is not essential to maintain SRB within the sediment. Anoxic conditions typically occur within lake and marine sediments close to the interface even if the water is not anoxic. This is due to the characteristically high oxygen demand of sediments, which thus provides the optimal environment for SRB metabolism. A review of SRB geochemistry by K.A. Perry follows as Section 1.3.

A set of recent reports and case histories on the geochemistry of tailings discharged to subaqueous *freshwater* environments is now available, having been commissioned by a government taskforce through the Mine Environmental Neutral Drainage (MEND) program (Table 1.1). Although these refer only to tailings discharged to lakes, and to land or river sites from which tailings entered lakes, the principles of their conclusions are relevant to STD.

One case history in particular, that of Benson Lake in British Columbia, provides important documentation on the comparative geochemistry of tailings discharged both on land and under water. The reports on Benson Lake, as in other lakes, provide documentation that tailings deposited in a low-oxygen aquatic condition released little or no trace metals (See Rescan, 1990, 1992). The essential absence of metal release from the subaqueous tailings deposit stands in marked contrast to the extensive leaching seen in the same tailings deposited on land, which have been subjected to weathering, rainfall and aeration. Note however that Benson Lake was a continuing cause of concern and regulatory action during the period of tailings discharge due to raised water turbidity (Rescan, 1989). The discharge was also accompanied by some smothering of the lake benthos. In 1992, 17 years after tailings discharge ceased, there had been no long-term evidence of effusion of metals from the continuously-submerged sulphide-rich deposits. The study concluded that this chemically benign condition should persist in the future.

The thrust of the MEND reports is that the virtually unlimited supply of oxygen in air, plus rainfall, makes onland deposition of potentially acid-waste generating tailings more environmentally risky over the very long-term than subaqueous disposal.

This conclusion differs from the conventional wisdom, undoubtedly correct at some sites, that mine tailings should not be discharged to river, lake or the sea. Even if they are not chemically toxic, subaqueous tailings discharges do have the potential to destroy habitat and biological resources. The impact may not be permanent as recovery can occur.

Such concerns were expressed in a critical review of the MEND studies (Rawson Academy, 1992). Nevetherless, the Rawson report stated:

> "Subaqueous disposal of tailings appears to offer physico-chemical advantages over terrestrial disposal, with respect to sulphur oxidation and the generation of acidic waters. Two separate mechanisms are evident in the documentation provided. These include oxide blocking and sulphide precipitation of mobile metals.
>
> Conceptually, the Scientific Review Team agreed that once buried under 5-10 cm or more of normal lake sediment, diffusional conditions will largely control the geochemical behaviour of tailings, and they would be relatively stable over the long term (assuming additional influences such as groundwater migration are negligible).

Table 1.1 Bibliography of the MEND Reports on the Geochemistry of Subaqueous Deposits of Mine Tailings.

Galbraith, Moira. 1989. Anderson and Mandy Lake 1989 vertical and horizontal tows. Rept. to Rescan Environmental Services Ltd.

Rescan Environmental Services Ltd. 1989. Subaqueous disposal of reactive mine wastes. Draft Rept. for B.C. Acid Mine Drainage Task Force.

Rescan Environmental Services Ltd. 1990a. A preliminary assessment of subaqueous tailings disposal in Benson Lake, British Columbia. Rept. to B.C. Min. of Energy, Mines and Petroleum Resources and others.

Rescan Environmental Services Ltd. 1990b A preliminary assessment of subaqueous tailings disposal in Anderson Lake, Manitoba. Rept to B.C. Min. of Energy, Mines and Petroleum Resources and others.

Rescan Environmental Services Ltd. 1990c Geochemical assessment of subaqueous tailings disposal in Buttle Lake, British Columbia. A B.C. Acid Mine Drainage Task Force Project. Rept. to B.C. Min. Energy, Mines and Petroleum Resources and others.

Rescan Environmental Services Ltd. 1990d. A preliminary assessment of subaqueous tailings disposal in Mandy Lake, Manitoba. Rept. for B.C. Min. Energy, Mines and Petroleum Resources and others.

Rescan Environmental Services Ltd. 1991. A preliminary biological and geochemical assessment of subaqueous tailings disposal in Benson Lake, British Columbia. Rept. to B.C. Min. of Energy, Mines and Petroleum Resources and others.

Rescan Environmental Services Ltd. 1992. Chemical diagenesis of submerged mine tailings in Benson Lake and natural sediments in Keogh Lake, Vancouver Island, B.C. Rept. to Placer Dome Inc.

The application of a single *generic* approach to subaqueous tailings disposal does not seem practical; for the most part, considerations (involving a range of economic political, technical and environmental factors, etc.) should be site-specific.

The MEND literature review of geochemical processes controlling metals release is excellent, it is well written and comprehensive (at the time of completion)."

Also, and in contrast to the conventional wisdom about marine disposal of wastes, the case histories of the Island Copper and Kitsault mines in Volume I support the conclusions of the MEND reports. Tailings discharged to depth there, in the sea as opposed to lakes, have not released environmentally significant quantities of trace metals. At Island Copper it is now known that there is some acid-generating potential (Lister *et al.*, 1983), thus geochemistry of the discharged tailings is significant and has been investigated (Pedersen and Losher, 1988; Pedersen, 1985).

In this volume the extra case histories documented for the development of Screening Criteria, allow placing the conclusions of the MEND reports into the context of STD and other forms of marine tailings disposal.

The findings of the MEND reports are already influencing Canadian regulatory policy on acid drainage control at mines. A draft "Interim Policy for Acid Rock Drainage at Mine Sites" (Anon, 1993) states (See also Table 1.2):

"Secure underwater disposal of tailings or waste rock in made-made structures is currently an acceptable form of acid rock drainage prevention. Underwater disposal in natural water bodies will only be considered where there is shown to be no significant impact on water quality, fisheries, recreation or downstream flow, and where the water bodies are shown to be the most environmentally suitable disposal site."

1.3 Sulphate-Reducing Bacteria and the Production of Sulphide (Author K.A. Perry)

1.3.1 Introduction

Dissimilatory sulphate reduction, in which sulphate is reduced in large excess of that required for cellular growth, is the primary means of organic carbon mineralization in anoxic marine waters and sediments. The sulphate-reducing bacteria are assigned to more than a dozen different genera (*i.e.* Desulfovibrio, Desulfotomaculum, Desulfomonas), and use sulphate as the terminal electron acceptor in the oxidation of either organic matter or molecular hydrogen:

$$SO_{42- + 2CH2}O + 2H^+ -> 2CO_2 + 2H_2O + H_2S$$

$$SO_{42- + 4H2} + 2H^+ -> 4H_2O + H_2S.$$

These reactions do not use up oxygen directly, but the H_2S generated is readily oxidized, which consumes oxygen in aerobic waters. Some SRB can also reduce sulphite, thiosulphate and colloidal sulphur (but not orthorhombic sulphur) (Widdel, 1988).

Table 1.2. Excerpt from a Draft "Interim Policy for Acid Rock Drainage at Mines Sites (Anon, 1993). (Note that this is a Draft statement).

PREVENTION OF ACID ROCK DRAINAGE

All mines with a potential for acid drainage must provide operational reclamation and abandonment plans showing how they will reduce the generation of acid drainage to levels not considered deleterious to the environment, both in the short or long term. In cases where the success of prevention measures cannot be assured, an assessment of the potential for failure and of the possible impacts will be required. Detailed contingency plans to reduce the risk to the environment will also be needed. This will usually consist of a collection and treatment system.

Material with one or more of the following properties shall not be used for roads, dams or other construction purposes:

* a total sulphur level greater than 0.5 percent;

* 0.1 to 0.5 percent total sulphur and an NP:AP of less than 4.1.

* a paste pH less than 5; and,

* a potential for significant losses of residual weathering products.

UNDERWATER DISPOSAL

Secure underwater disposal of tailings or waste rock in man-made structures is currently an acceptable form of acid rock drainage prevention. Underwater disposal in natural water bodies will only be considered where there is shown to be no significant impact on water quality, fisheries, recreation or downstream flow, and where the water bodies are shown to be the most environmentally suitable disposal site.

Further research is required to assess the impact of the underwater disposal of tailings or waste rock in biologically or water quality sensitive lakes before this disposal alternative will be considered.

In cases where underwater disposal of tailings or waste rock is proposed, the proponent must show that:

* the mine wastes do not contain significant readily soluble deleterious substances;

* the water balance ensures that all potentially acid generating wastes will be continuously covered by the water; and

* there will be no significant impact as a result of wave action, ice, avalanches, flooding, earthquakes, thermal overturn and other relevant natural factors.

Man-made impoundments shall be designed and maintained for long-term geotechnical stability taking into account the possible effects of biological activity.

A water cover is currently an acceptable form of acid rock drainage prevention for underground workings or open pits.

The timing and inflow rate requirements in flooding open pits and underground workings will be based on the hydrologic conditions, the relative reaction rates of acid generation versus neutralization and the potential release of acid products. Proponents must demonstrate that any water released to the environment will be of acceptable quality. Hydraulic bulkheads or material barriers in underground workings shall be designed to allow ongoing verification of the water level and of geotechnical stability.

The growth physiology of SRB reflects their distribution and role in nature. They require an environment in which organic substrates and dissolved sulphate are available. Although the absence of O_2 is no longer deemed necessary for sulphate reduction, SRB are found in greatest numbers in anaerobic environments. The availability of oxygen for biological degradation processes in water is limited by the solubility of this gas. If organic matter accumulates in aquatic environments, oxygen becomes depleted rather quickly; the degradation of the biomass is then taken over by anaerobic bacterial communities, a part of which are SRB.

1.3.2 Ecology and Distribution

SRB are unique in their almost universal distribution and are adaptable to almost any environment. Representatives of SRB are found in soils; fresh, marine and brackish waters; artesian waters; hot springs and geothermal areas; oil and natural gas wells; sulphur deposits; estuarine muds; sewage; salt pans; corroding iron; the rumina of sheep and huts of insects. They tolerate temperatures from below -5 to 75°C and adapt easily to temperature changes; they can be grown under pressures of 1 x 10^5kPa; they tolerate pH values ranging from below 5 to 9.5 and a wide range of osmotic conditions (Postgate 1984). The majority of SRB in nature function below 5°C rather than above, due to their abundance in ocean sediments. SRB can survive long exposure to oxygen and become active again when anoxic conditions return. SRB are rarely encountered as airborne organisms, though both sporulating and non-sporulating strains survive drying in soils. Most SRB can grow with sulphite or thiosulphate as electron acceptors instead of sulphate. Growth of SRB with elemental sulphur has also been observed. Other alternate electron acceptors used by some SRB include nitrate and fumarate. Various SRB species can disproportionate sulphite and thiosulphate to form sulphate and sulphide. Acetate serves merely as an organic carbon source for cell synthesis. Some varieties can also ferment organic substrates.

1.3.3 Carbon Sources (Electron Donors)

SRB can metabolize a wide variety of organic compounds as well as a few inorganic compounds. The carbon sources oxidized by SRB are always low-molecular-weight compounds, nearly all of which are fermentation products from the anaerobic bacterial degradation of carbohydrates, proteins, and other components of dead biomass by bacteria other than SRB (Widdel, 1988). Some species oxidize substrates incompletely to acetate while others are capable of oxidizing their organic substrates, including acetate, completely to carbon dioxide. Generally, the incompletely oxidizing SRB are nutritionally less versatile, although they grow more quickly than the completely oxidizing species. Sorensen *et al.* (1981) found the quantitative contribution of the most commonly used substrates to sulphate reduction in marine sediments to be: acetate (40-65%), propionate (10-20%), butyrate (5-20%), isobutyrate (8%) and hydrogen (5-10%). If the oxidation of butyrate and propionate is incomplete, however, then acetate oxidation can account for almost two-thirds of the sulphate reduction occurring in the sediments.

Very few types of SRB are known to use methanol or methoxyl groups from aromatic compounds and a utilization of methylamines or methionine by SRB has never been observed. Some dispute has centered on whether hydrocarbons, such as methane or higher petroleum hydrocarbons, are utilized for growth; the balance of evidence is that they are not utilized by any known type of SRB. However, ecological evidence suggests that species or consortia capable of such reactions may exist (Widdel, 1988).

The range of substrates used by SRB as carbon sources for growth is thus fairly narrow: a few C2-and C3- and C4- substituted fatty acids--such as acetate, lactate, pyruvate, fumarate or malate--are widely used, glycerol and certain simple alcohols being less good substrates. A very few desulfovibrios and desulfotomacula can utilize carbohydrates such as glucose or sucrose.

1.3.4 Other Nutritional Needs

All SRB can be cultivated in defined media without complex supplements such as yeast extract, although its addition may stimulate growth. A few vitamins as growth factors may be the only supplements required (Postgate, 1984). Therefore SRB are able to synthesize all of their cell material from the same organic compounds used as electron donors, and in addition from carbon dioxide.

1.3.5 Metabolism of Iron

Some *Desulfovibrio* species show an exceptionally high requirement for inorganic iron. *Desulfovibrio* contains large amounts of iron-rich proteins such as ferredoxins, cytochromes of the c3 group, and nitrogenase and, in iron-starved cultures, the content of cytochromes c is less. This large need for iron is unusual since, in sulphidic solutions, Fe^{2+} is quantitatively removed from solution as FeS and FeS_2 which have very low solubilities. Several amino acids and peptides chelate Fe^{2+} and thus inhibit precipitation of FeS. It is likely that apparent nutritional effects of amino acids and such materials simply reflect their ability to make Fe^{2+} more readily available (Postgate, 1984).

1.3.6 Environmental Factors

1.3.6.1 Effects of Oxygen

Several recent studies have shown that some SRB are not only oxygen tolerant, but actually have a capacity to reduce O_2 to H_2O (Cypionka *et al.*,1985; Dilling and Cypionka, 1990) Studies of anoxic basins (Hastings and Emerson, 1988), salt marsh sediments (Howarth and Giblin, 1983) and cyanobacterial mats (Canfield and Des Marais, 1991) have all demonstrated environments where SRB are concentrated in zones of maximum O_2 concentration. It has been suggested that this is because these zones are also areas of maximum electron donor concentrations, thought to be the major limiting factor for SRB in several environments.

Two laboratory studies have examined the effects of O_2 on pure cultures of SRB. Hardy and Hamilton (1981) examined five strains of *Desulfovibrio vulgaris*, previously isolated from North Sea water for their abilities to survive in aerobic natural seawater. Viable organisms of all strains were recoverable after exposure to oxygen for more than 72 hours. They found an equivalent decline in viable numbers of SRB in both aerobic and anaerobic vessels implying that oxygen *per se* has no greater bactericidal effect than did suspending the cells in an anaerobic environment unfavorable for growth. The possession of oxygen-protective enzymes such as superoxide dismutase and catalase enables SRB to survive in oxygenated seawater at levels of

10^1 -10^2 ml^{-1} (Hardy and Hamilton, 1981). The autoxidizable nature of cytochrome $\underline{c}_3$ and KCN-inhibitable cytochrome $\underline{c}$ oxidase activity present in these bacteria were postulated to act as possible oxygen-scavenging mechanisms analogous to the activity of NADH oxidase present in certain other strict anaerobes.

It has also been shown with pure cultures that species of SRB differ significantly with respect to oxygen sensitivity. Cypionka *et al.* (1985) studied the survival after oxygen stress of eight species of SRB. In the absence of sulphide, all species tolerated six minutes of aeration without loss of viability. Even after three hours of aeration the viability of four species (*Desulfovibrio vulgaris, D. desulfuricans, D. salexigens and Desulfobacter postgatei*) in an oxygenated, reductant-free medium was not impaired. Four other species were sensitive to three hours of aeration; the surviving fractions of *Desulfotomaculum ruminis, D. nigrificans and Desulfococcus multivorans* were about 1%, that of *Desulfococcus orientis* about 0.01%. Formation of spores resulted in oxygen resistance of *D. orientis*. Reducing agents did not protect the vegetative cells of this strain against oxygen toxicity. In contrast, sulfhydryl group-containing agents including sulphide increased the sensitivity to oxygen considerably.

Cypionka *et al.* (1985) also studied the growth of SRB in oxygen-sulphide gradients in agar tubes and found that SRB grow in the absence of sulphate. SRB that could not use thiosulphate (S_2O32-) or elemental sulphur (So) as electron acceptors failed to grow in oxygen-sulphide gradients. As indicated by the added redox indicator resazurine, molecular oxygen did not directly serve as electron acceptor in these experiments. The reaction of oxygen with sulphide provided oxidation products that could be reduced back to sulphide by SRB. Sulphur, thiosulphate and sulphate are known to be the main products of autoxidation of sulphide, with So dominating in acidic solutions and thiosulphate at basic pH (Cline, 1969; Sorokin, 1972; Chen and Morris, 1972b; Chen and Morris, 1972a; Jorgensen, 1982). The oxidation products of sulphide were used as electron acceptors and were continuously regenerated in a cycling process from sulphide by autoxidation. In natural environments sulphide may also be reoxidized by sulphur-oxidizing bacteria which produce sulphate.

If aerobic sediments or waters are rich in organic particles, SRB may be active in anaerobic microniches. Jorgensen (1977) measured sulphate reduction in the upper oxidized marine sediment layer and also in detritus particles suspended in oxic seawater. In the oxic sediment, 2 x 102 colony-forming units of lactate-utilizing SRB were determined. The sulphate reduction took place in reduced organic-rich sediment pellets 50 to 200 um in diameter. The anaerobic microniches are formed and maintained by scavenging of oxygen by aerobic organisms in the degradation of the locally high concentrations of organic matter. The end product of SRB, sulphide, also consumes oxygen.

In general, if a habitat becomes homogeneously oxic over a long period, vegetative cells of SRB die off, and only spores of *Desulfotomaculum* species survive. Therefore, these species may be selectively enriched from dry or oxic soil samples. If an environment turns from aerobic to anaerobic conditions, desulfotomacula are expected to be the first active SRB, and a selection of these species due to dry periods has been observed in paddy fields (Postgate, 1984).

Therefore, SRB show a reasonable tolerance to the presence of oxygen. SRB differ from other anaerobes in that they produce a chemically reactive reducing agent. Sulphide traps oxygen and provides a low, favorable redox potential. Additional to the function of sulphide as reducing agent, its reaction with oxygen may provide an electron acceptor for sulphate- or sulphur-reducing bacteria in a cycling process. Recent studies have shown that SRB can grow in environments replete with O2. One of the reasons that SRB have traditionally been thought to be O_2 -intolerant may be that the enrichment processes used to isolate SRB selects for those varieties which are strict anaerobes.

1.3.6.2 Temperature and Salinity

SRB are found in natural waters of all salinities from near zero to saturation. The sulphate reduction rate in sediments strongly depends on the temperature, the effect of which within a certain range is described by the Arrhenius equation. The Q_{10} values reported for sulphate reduction in marine sediments range between 2.0 and 3.9 (Jorgensen, 1977; Nedwell, 1982) (*i.e.* a temperature increase of 10°C stimulates the sulphate reduction rate 2.0 to 3.9 fold). Although SRB will grow more quickly at elevated temperatures, it should be noted that the bulk of the world's sulphate reduction occurs in ocean sediments at temperatures of less than 5°C.

1.3.6.3 Effect of pH

Sulphate reducers prefer an environment around pH 7 and are usually inhibited at pH values lower than 6 or higher than 9; changing of the pH with acid or alkali has been suggested as a method of diminishing sulphate reduction in industrial plants (Postgate, 1984). However, sulphate reduction has been observed in peat bogs and in acid mine water that exhibited pH values of 3 to 4, although it was suggested that SRB in the acid environments occurred in microniches of a higher, more favorable pH. SRB are definitely found in waters with pHs of 5 and 6.

In summary, SRB are active under a wide range of environmental conditions. Their flexibility has caused them to be a nuisance organism in several industries, particularly in the oil industry. The genus *Desulfovibrio* shows extraordinary resistance to conventional bacterial inhibitors such as phenolics, quaternaries, antibiotics and metals. The ineffectiveness of metals is largely due to the ability of the organism to precipitate Hg^{2+}, Cu^{2+}, Cd^{2+}, etc. as sulphides; in the absence of H_2S these metals can be fairly toxic. Air has been found to be the cheapest and most effective inhibitor. The SRB will not be killed but they will remain dormant. As noted before, SRB alter environmental conditions to favor themselves by generating H_2S, neutralizing useful inhibitors such as chromate and oxygen.

1.3.7 Association with Other Anaerobic Bacteria

SRB exist within a consortium of anaerobic bacteria in which dynamic, complicated interactions occur among bacterial communities carrying out methane production and various fermentations along with sulphate reduction. SRB do not degrade natural biopolymers such as starch, glycogen, and proteins or lipids and are only capable of utilizing low molecular weight carbon compounds. Therefore, the presence of fermenting bacteria is required to break down more complex organic matter to simpler organic acids and alcohols before SRB can begin to grow.

Zones of sulphate reduction are often the foci of sulfureta, in which other sulphur bacteria grow in association with SRB. Such zones are common in deep stratified lakes and fjords. Above that zone, dissolved sulphide and dissolved air co-exist and aerobic sulphide-oxidizing bacteria (*e.g. Beggiatoa, Thiovulum*) may be found as well as thiobacilli. These organisms oxidize reduced sulphur back to sulphate and by thus recycling sulphur then tend to perpetuate the sulfuretum; by their autotrophic and photosynthetic CO_2 fixation they also regenerate organic matter. The occurrence and distribution of the sulphur bacteria are restricted by Eh and pH conditions, according to the amount of O_2 present and the oxidation state of the sulphur compounds. The specific requirements for growth of sulphur bacteria often result in distinct, thin layers of certain bacterial populations in the water columns of stratified lakes. The photosynthetic purple bacteria are often found in a dense layer immediately at the oxic/anoxic interface in meromictic lakes, below which a thin band of green sulphur bacteria dominates (Northcote and Hall, 1983). Light levels at bacteria-sustaining interfaces are usually about 10% of those at the surface (Pfennig and Widdel, 1982). Since SRB generate sulphide and the oxidizers fix CO_2, sulfureta act as anaerobic zones of primary production, similar to the photosynthesis of plants in aerobic environments. However, sulfureta are limited by the amount of either sulphide (for CO_2 fixation) or pre-formed organic matter (for H_2S formation) (Postgate, 1984).

1.4 Very Deep STD

1.4.1 Introduction

There is potential in the development of some coastal mines for Very Deep STD as a means of disposing of tailings. The Misima mine in Papua New Guinea (Ch. 2) is now in operation discharging at 118 meters on a steep dropoff (Hughes, 1989) extending beyond 1000 meters depth. Other prospective mines are exploring such disposal elsewhere. The history of environmental problems at Marcopper Mine, the Philippines (Ch.5.2), and Bougainville mine, PNG (Ch. 5.3) might have been avoided by the Very Deep STD possible at both sites.

The concept of Very Deep STD is based on discharge at the edge of an extended drop-off, say to 1000 meters, and at a depth below the euphotic zone. Discharge must be at a location where the tailings slurry from the pipeline will form a turbidity current flowing coherently with minimum dispersal until it reaches the base of the drop-off. Submarine canyons or naturally excised channels beyond fringing coral reefs in principle are suitable sites.
There must be very little or no risk at the site of impacting amounts of the tailings upwelling back into shallow water.

There is unfortunately virtually no environmental information in the public domain about the existing cases. Misima has extensive shallow water data (showing no upwelling with shallow impact - Hughes, 1989), but not data from the drop-off.

Tailings in the sea have been explored in a limited way in the literature of deep sea mining (Hammer *et al.*, 1993; Thiel *et al.*, 1991; Thiel, 1991), but open water disposal from a shipboard mill creates a dispersing plume, not turbidity currents in the manner of coastal tailings discharges.

Turbidity current flow can be monitored (Hay *et al.*, 1982, 1983a & b), modeled, and the deposition pattern and rate predicted (Hesse and Reim, 1993). Mathematical models need checking by real data. At the moment there are no data from tailings density currents at great depths.

1.4.2 Deep Disposal of Red Muds from Aluminum Smelters

There are however data on deep anthropogenic turbidity currents in the literature, but these are not tailings-derived. Surprisingly this readily available information is some 20-30 years old (Bourcier and Zibrowius, 1973). It concerns the deep discharges of *red muds* (boues rouge) from aluminum smelters in the Mediterranean Sea. These wastes, derived from a soda-bauxite reaction in the smelter, are rendered inert by the action of sea-water on residual soda. The two best described discharges are from outfalls at 320 and 330 meters depth, 5.6 km offshore, to the Canyon de la Cassidaigne, near Marseille. The turbidity current has been tracked to 1200 meters depth. Discharge started in 1967 and continues to the present at a rate of 1.5 million tonnes per year.

The original environmental impact information was gathered during 1967 - 1971 during the hey-day of manned submersible development by French engineers and scientists. Cousteau's diving saucers were available, and his team had fortuitously previously investigated and described the discharge site.

Some extraordinarily prescient observations were made and conclusions drawn in the 1970s. These had not been paralleled elsewhere, until STD (to shallower water) was well established in the late 1980s at Island Copper Mine. For this reason we provide a translation of impact details not otherwise available in the Anglophone literature.

1.4.3 Translation of Section 7, Benthic Life in Contact with *red mud* (Bourcier and Zibrowius, 1973)

"After the reaction of sea water on the soluble soda (neutralization effect) the *red muds* are simply inert and soluble suspensions in sea water. They are not toxic and their effect on the benthos is entirely mechanical.

In the centre of the canyon, the area of deep deposit and flow of the *red mud*, the benthic fauna is buried. Soon after the start-up of the first outfall (Pechiney), the dredge hauls showed that the macrobenthic species in the center of the canyon had disappeared, eliminated by the very fluid flow which quickly builds up to a considerable thickness. For the same reason the new substrate, being unstable, cannot be recolonized by new macrobenthic larval species from elsewhere. In December 1968 the sampling area was extended from the original zone at the end of the outfall to a depth of 1,200 meters to the south just before a narrow sill (about 960 meters) giving on to the abyssal plain. The zone did not exceed 1.6 km in width (Bourcier, 1970).

Obviously, we do not have any observations of the depths beyond the windows of the diving saucer SP350. Only use of the diving saucer SP3000 can confirm these findings and bring about modifications. A survey of the whole basin, situated before the narrowing and the sill will eventually show the level of survival of the sessile fauna attached to the rocky substrate sticking out of the thick covering of *red mud* and in less turbid water.

However, the areas on the sides of the main deposits where the deposit of *red mud* is less rapid (between a millimeter and a centimeter), explored by the diving saucer SP350, the benthos does not seem to be affected. We have actually observed a rich and varied fauna corresponding to what could be expected at these depths in the Mediterranean according to previous studies of bathyal fauna. The benthic fauna observed in the Cassidaigne canyon in June 1971 did not seem to have diminished or to have noticeably been modified since the previous observations taken over the same route between 1960 and 1965 (Laborel *et al.*, 1961, Vacelet, 1968) long before the start of *red mud* discharge.

During all the dives we noticed an abundance of burrows at all levels down to the deepest level reached, where the covering by *red mud* was of any importance (370 meters depth). The activity of the animals building and inhabiting those burrows (probably crustacea, rarely seen), and the action of fish (burrowing, and swimming close to the sediment) contribute largely to the mixing of the *red mud* with the sediment. The natural sediment thrown up by the burrowing animals is grey and contrasts to a greater or lesser extent with the surface layer which is already more or less mixed with the *red muds*.

During the dives in areas not yet affected or only slightly affected by the *red muds* (dive #1 in an Eastern direction, dive #2 on the continental shelf, dive #5 on the upper part of the northern slope), the appearance of the first traces of *red muds* was difficult to see, because of the contrast between the surface and deeper sediments. It is probably easier to discern faint traces by dredging (skimming the sediment).

In the zones affected by the *red muds* we have observed the feeding methods of different macrobenthic species particularly the ingestion of raw sediment, the ingestion of particles by raking the surface of the sediment, or, just beneath the surface, passive and active filtration. All these feeding methods and collection methods involve their digestive tube being in direct contact with *red mud* particles.

The large Aspidochirote holothurians, *Stichopus regalis* Cuvier and *Holothuria* sp., which we have noticed at various depths on sediments more or less mixed or covered with *red muds*, ingest the raw sediments. Their faeces, which can be seen, are the same colour as the sediment. We have also seen many specimens (*Holothuria* sp.) on a sloping rockface with a thin layer of completely red sediment (210 meters).

Our dredge hauls have already given us Sipunculids (*Golfingia minuta* (Keferstein)) and Polychaetes (particularly Maldanidae) with digestive tubes entirely filled with a sediment definitely red, in the same way sea urchins (*Brissopsis lyrifera* Forbes) often have a mixture of sediment and red mud in the stomach contents.

Among the representatives of the second category they have a choice of food particles (detritus, Foraminifera, post larval stages of Molluscs, different meiofauna, etc) including various species of Ophiuroids with the oral side upwards with their legs on the bottom, the Echiuroids (probosces of *Bonellia viridis* Rolando spread out on the surface), the Polychaetes Terebellidae with irregular tentacles spread over the sediment (leaving, after retracting, faint furrows in the sediment), certain Crustacea Decapoda (Pagurids, Crabs) as well as the Scaphopoda (these last found in dredge hauls.)

The passive filter feeders which trap by means of a large surface area (a plume of tentacles or arms) particles and detritus, or zooplankton, in seawater loaded, at least temporarily, with *red mud*, exist at all the depths investigated, also in the areas with a thick covering of *red muds*: Polychaetes Sabellidae and Serpulidae, Crinoids (*Leptometra phalangium* Forbes), Bryozoans, Hydroids and Anthozoans. There were also the active filter feeders passing vast quantities of water through their systems (Sponges, Brachiopods, Molluscs, Pelecypods, Ascidians). In general, the *red mud* particles seem to be eliminated normally like any other non-edible particle. All the same, in certain cases the extremely fine red mud particles ingested and apparently taken up in the digestive tract, can accumulate inside the organisms: *red muds* in the *brown body* of Bryozoan *Scrupocellaria* sp. (observation by J.G. Harmelin on material from our dredge hauls: photo 10).

Fish respiration does not seem to be affected by the *red mud* particles in suspension (raised by fish activity, burrowing and swimming near the bottom, or temporarily resuspended by the current.) In the zones affected by the *red muds*, we observed a number of nectobenthic bottom dwelling and deep sea fish and their behaviour appears to be normal."

1.4.4 Other Relevant Deep Sea Information

In recent years there has been considerable progress in understanding the structure and dynamics of deep-sea ecosystems (Sibuet, 1992; Tilot, 1992; Pentreath *et al.* 1988; Sibuet, 1987; Sibuet and Juniper, 1986), and with it the potential for developing environmental impact assessments on deep tailings turbidity currents. Five phenomena seem to be of particular importance in this context: abyssal "storms," turbidity currents and slumps of perched deposits, recolonization of destabilised areas, seasonal changes in natural abyssal deposition, and marine snow.

1.4.4.1 Abyssal Storms

The HEBBLE site experiments in the early 1980s (Hollister and Nowell, 1991) demonstrated that the abyssal plain is not always a calm place (Gross and Dade, 1991). There are occasional physical disturbances, *abyssal storms*, which erode, resuspend and transport deposits. As the storms fade or pass on, so materials are redeposited. Meiofaunal isopods and harpacticoid copepods, for example, are reduced, but can recolonise. There appears to be some relationship with atmospheric storms, implying physical mechanisms for energy transfer from surface to depth (with associated vertically moving disturbances).

1.4.4.2 Turbidity Currents and Slumps of Perched Deposits

Turbidity currents and their deposits are well established as occurring at great depth, and have been associated on occasions with slumps of perched deposits (McCave and Jones, 1988; Krank, 1984). There are some obvious implications here that an anthropogenic turbidity current might cause some destabilization on continental slopes, with resuspension and biological consequences within the broad-front flow path of the slump.

1.4.4.3 Recolonization Potential (from Tailings Deposition)

Sibuet (1992), Tilot (1992), Pentreath *et al.* (1988), Sibuet (1987), Sibuet and Juniper (1986) between them make it clear that recolonization occurs on abyssal plains (*i.e.* after stabilization of slumps), and near active deep vents. See also Bird and Holdich (1989), Snelgrove *et al.* (1992), and Thiel (1992).

However, in the deep sea normally deposition is very slow. Tilot (1992) uses 3-8 cm/1000 years as the baseline level.

Marine tailings deposition can be very much greater than that, ranging up to (and presumably greater than) the known 40 meters over 20 years at Island Copper Mine (Ch. 3, Volume I). At the fringe of such thick, rapidly depositing tailings beds there are areas subjected to much slower and less deposition. At Island Copper Mine the fringe areas have received as little as 1 cm per year over 20 years. Beyond the visible fringe there is a further margin where tailings are not visible in core samples, but can be detected by chemical measures of copper levels (e.g. >100 ppm) (Island Copper, 1992).

There has been some development of knowledge about the colonization of relatively shallow fjord sediments affected slowly or rapidly by mine tailings (Ellis and Hoover, 1990, 1991; Ellis and Taylor, 1988). In summary, after catastrophic smothering of normal fjord benthos, a productive benthic ecosystem appears following the first summer larval spatfall, provided the deposited tailings are stable. At Island Copper mine after 20 years of slow deposition at locations with little tailings, (*i.e.* about 1 cm per year), the infaunal benthos remains not distinguishable from adjacent areas without visible tailings (I.C., 1992). At Britannia Beach the recovered abundant benthos was nevertheless measurably different from a reference site (Ellis & Hoover 1990) 12 years after mine closure. The essence of the recent research is that there can be recovery to a productive ecosystem within one or two years, but not necessarily to the same association of species as that originally present.

In the context of the deep sea even a 1 cm p.a. settling rate at the edges of a tailings field might have impacts on seabed biology, although the *red mud* observations do not support this, showing deep deposit feeders alive and ingesting the deposits.

1.4.4.4 Seasonal Changes in Natural Abyssal Deposition

It is now known that there are seasonal changes in the rate at which particles arrive on the abyssal sea-bed (Linke, 1992; Martin and Bender, 1988). This affects the food network; from microscopic foraminifera through a range of larger organisms such as isopods, echinoderms and molluscs. There is some relationship with surface events and seasonal conditions. Thus there appears to be adaptative capability by deep sea faunas to varying rates of food deposition.

1.4.4.5 *Marine Snow*

Marine snow consists of bacterial and detrital macroflocs and stringers (Alldredge & McGillivray, 1991, Amy *et al.*, 1987) larger than about 0.5 mm. The snow appears to be widespread both at surface and depth, and may represent an important materials and energy flow route to, and in, the deep sea ecosystem. Marine snow forms around a physical nucleus, and may be resistant to disaggregation.

Mine tailings have not been investigated as physical nucleii for marine snow formation as far as we know. Nevertheless, submersible observations of flocculent stringers underwater near Island Copper Mine (Ellis and Heim, 1985) suggest that tailings can act in that way. Thus suspension and resuspension of large amounts of tailings at great depth could have effects on the deep sea bacterial system. This potential for presently unknown effects merits some investigation.

2.0 THE MISIMA GOLD AND SILVER MINE (PAPUA NEW GUINEA)

2.1 Introduction

The Misima gold and silver mine is located on Misima Island, one of the most southerly islands of Papua New Guinea (PNG) (Figure 2.1). The mine is important in the context of STD for a number of reasons.

(1) It was the first case outside Canada (after Island Copper and Kitsault - See Volume I, chapters 3 and 4) in which the exploration of STD as a tailings disposal option was publicly documented from concept, through construction, to operations.

(2) The STD involved is the first example of Very Deep STD, utilizing an engineered sea-water mixing outfall discharging to a slope leading to abyssal depths of more than a thousand meters (Fig.2.2).

(3) The milling process involves addition and subsequent disposal of cyanide, for which special environmental precautions need to be taken.

(4) The mine has to dispose of rock waste, part of which is soft rock that cannot be engineered into stable on-land dumps. Accordingly, the soft rock is dumped at a shoreline site, and its marine environmental impact needs assessments to distinguish it from that of the STD.

(5) Misima is one of several coastal mines being developed in PNG (Hughes and Sullivan, 1989, 1991). The environmental assessments, predictions and monitoring can and do function as role models for other mines there and elsewhere in the South Pacific Region.

The mine was permitted in 1987, under the terms of the Water Resources Act 1982 (Rescan, 1993), and began operations in 1989 (Table 2.1). Mine lifetime is expected to be about 10 years, with total production of 77.2 and 1,175 tonnes of gold and silver respectively. Tailings production is at the rate of approximately 18,000 tonnes per day. Previous operations on and near the site had included alluvial workings (deposits discovered in 1888), and an underground mine (1915-1942).

2.2 The Orebody

The gold and silver-lead-zinc mineralization lies mostly within a NW trending belt (5 km x 4.5 km) at the center of the eastern end of the island.

The most important lode gold mineralization occurs in a large number of mineralized faults. These vary in size from narrow fractures to major breccia zones more than 10 meters in width, having strike lengths which may exceed 1,500 m. Branching and en

Figure 2.1 - Map of Misima Island, Showing the Location of the Mine, and the Location of Misima Island in Papua New Guinea (Reprinted and modified from NSR, 1984).

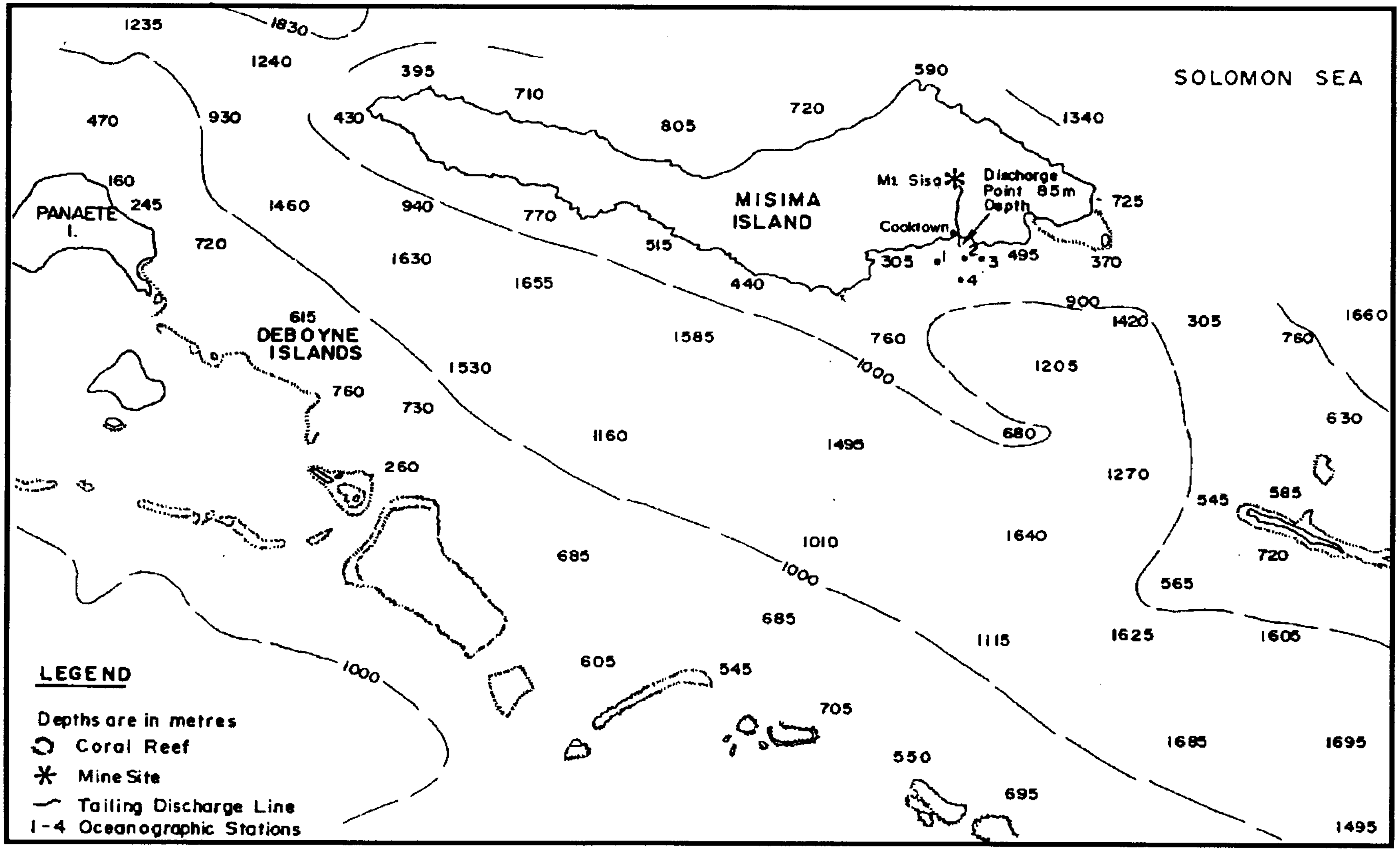

Figure 2.2 - Bathymetry near Misima Island (Reprinted and modified from Rescan, 1982).

Table 2.1. Timing of the Misima Gold and Silver Mine Development.

1888 Discovery of alluvial gold on Misima Island.
Approx. 100,000 ounces gold produced

1904 Discovery of lode in headwaters of Cooktown Creek

1915-1942 Underground mine operating at rate of about 100 tons of ore per day. During wartime abandonment, extensive collapse of underground workings prevented later re-opening. Combined alluvial and underground gold output during this period about 150,000 ounces.

1978 The PNG Environment Planning Act places requirements on new resource developments, including regulatory agency option for an Environment Plan.

1982 Environmental investigations initiated.

1987 Mine Environment Plan (NSR, 1987) approved by the regulatory agency, and a Water Use Permit for the STD system issued under terms of the Water Resources Act 1982 (Rescan, 1993). This permit cross-references seven other relevant permits.

1989 Operations commenced, with expected lifetime of 10 years.

echelon mineralized faults form lode systems, the largest of which is the Umuna lode system.

Typically the mineralized faults are deeply oxidized and contain very fine-grained free gold. Past mining at Umuna was carried out entirely in sandy, friable lodes of this nature, and consequently they are referred to as Umuna-type lodes. The average lode width mined was 5 m, and a total of 127,000 fine ounces of gold were recovered from an estimated 400,000 tons of ore, at an indicated recovered grade of 9.5 g/tonne. Average values of 1.5 g Au/tonne are common in shattered wallrock for distances up to 10 meters from the friable lodes, with locally much higher values, and this wallrock mineralization adds significantly to tonnages for any large, low grade mining venture. In the past, silver production averaged about three times that of gold." (NSR, 1982)

The total ore to be extracted is 56 million tonnes (Mt) at a stripping ratio of 1.2 tonnes of waste to each tonne of ore... The mineable ore reserve will sustain the operation for 13 years at a planned production rate of 4.5 Mt per year.

Mining will be by conventional open pit techniques. The deposit will be mined in a series of economic stages in which those parts of the ore body with higher than average grades and low strip ratios are mined first. Pre-stripping to remove vegetation will be carried out first and this will be restricted in area to minimize erosion of the underlying soil. Mining will be carried out simultaneously along a number of horizontal benches by first drilling and blasting and then removal by hydraulic shovels loading large haul trucks...." (NSR, 1986)

2.3 Mineral Processing

The ore treatment plant will be a conventional gold cyanidation plant with gold recovery by the carbon-in-pulp process. The ore will be ground in a ball mill to a diameter of 125-235 micrometers. The tailing left after gold and silver have been extracted will consist of a mixture of water, mud and chemicals such as cyanide used in the extraction process. This tailing will flow to a mixing tank where it will be diluted with sea water to reduce the residual cyanide concentration to a level acceptable for deep ocean discharge down a pipeline" (Hughes, 1989). A simplifed plant flowsheet is provided as Figure 2.3.

In the context of the waste discharge, process cyanide is of particular importance:

To recover residual cyanide in solution, the CIP tailing will be washed counter-currently in three 21.3 meters diameter CCD thickeners. At 1:1 wash ratio, about 75% of the reagents will be removed from the slurry for reuse in the plant. The first stage counter current decantation (CCD) thickener overflow will be pumped to the reclaim water pond. Reclaim water will be reused in the grinding circuit. The third stage CCD thickener underflow will form the final tailing." (NSR, 1986)

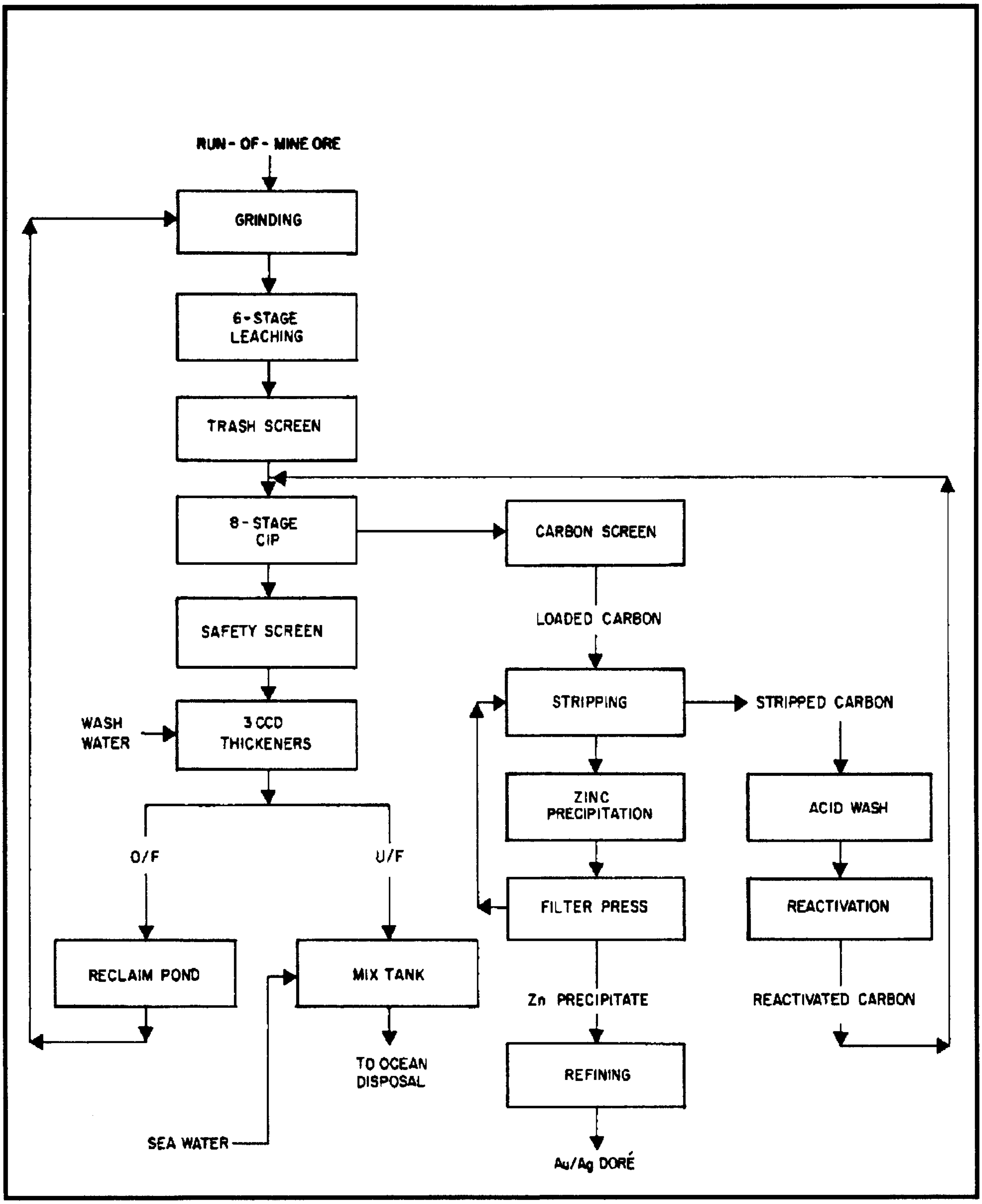

Figure 2.3 - Simplified Process Flow Sheet for the Misima Mine (Reprinted and modified from NSR, 1986).

2.4 Waste Discharge Characteristics

The original waste discharge requirements as set by the permit are documented in Table 2.2. The cyanide levels are clearly stated. The accompanying notes specify that the stated levels shall not be exceeded at any time. Also note that the Environmental Plan (NSR 1987) includes a sea-water mix system giving a dilution of greater than 10,000:1 at the boundary of the permitted mixing zone (Rescan 1993).

Sewage wastes may be added to the tailings discharge, but in fact were not added (Murray, personal communication).

In addition to tailings, 35 Mt each of hard and soft rock waste need disposal in some environmentally benign manner.

The hard rock waste can be stored in stable dumps on land (selected as largely unproductive for subsistance resource use). About 60% of the hard rock would be placed in this way (Figure 2.4). The remaining 40% would be used to back-fill one end of the pit. Acid waste generation was not considered a problem (NSR, 1987) on the basis of ABA and bacterial leaching tests (Murray, personal communication).

The 35 Mt of soft rock waste was not storable in stable dumps on-land. Three disposal options were considered: dam containment, milling for discharge with the tailings, and shoreline dumping. The latter was chosen (Figure 2.5) as substantially cheaper than the other options, even with compensation to local resource users. The choice was also based on a prediction of restricted environmental damage (Figure 2.6) and recovery after mine closure. There had been a recovery of the marine environment (fishery resources and coral reefs) from the erosional, washout, smothering and contamination effects of the prior 50 years of underground and alluvial mining abandoned in 1942 (NSR, 1987).

2.5 Tailings Disposal System

The proposed tailings disposal system is illustrated in Figure 2.7, and was subsequently constructed as follows:

> Tailings from the Misima mill is piped as a slurry (50% solids by weight) to the seawater mix tank. At the mixtank, seawater drawn from a depth of 60 meters mixes with the tailing slurry at a nominal ratio of about 7 parts seawater to one part slurry. The resulting mixture has a specific gravity of about 1.07 compared with about 1.02 for seawater. This density differential drives the discharge through an outfall pipeline that terminates at a depth of 118 meters on a steeply sloped (>45°) seabed" (Rescan 1990).

The outfall terminus at 118 meters depth is about 200 meters from shore (Figure 2.8).

The STD system was subjected to two separate Compliance Validation assessments in July and December 1989 soon after startup. Dilution calculations by dissolved copper analyses (Figure 2.8) and suspended solids profiles gave calculated dilutions 1200 meters distant at the boundary of the mixing zone (the plume compliance line in Figure 2.8) usually from the required 10,000:1

Table 2.2. Waste Discharge Characteristics for the Misima Mine Extracted from Water Discharge Permit No 29/336, 1987.

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1. Discharge approximately 56 million tonnes of treated mill tailings into the Solomon sea via a deep sea outfall at 100m depth, and in accordance with the approved Environmental Plan for the Misima Gold Mine Development (1987).

2. The discharge location shall be at 100m depth below mean sea level and in the area defined in the Environmental Plan.

3. That on a basis of 24 hour composite samples the components of the effluent to the mixtank, as specified by the Permit Holder, shall not exceed the following concentration at any time.

Component	Maximum (Micrograms per Liter)
Arsenic	2.0
Cadmium	43
Copper	20,500
Iron	258
Lead	170
Mercury	0.75
Nickel	195
Silver	7,475
Zinc	55,000
Total Cyanide	125,000
WAD Cyanide	88,300
SCN	21,600

Sewage wastes	Unspecified

Table 2.2. Waste Discharge Characteristics for the Misima Mine Extracted from Water Discharge Permit No 29/336, 1987. Contd.

Note: All metal concentrations are for dissolved metals (passing a nominal 0.45 mm millipore filter)
WAD - Weak Acid Dissociable
SCN - Thiocyanate

4. That except as listed above, no other plant generated effluent shall be discharged without prior written approval from the Water Resources Board.

5. The mixing zone boundry is defined as a horizontal plane at 70m depth below sea level from the outfall alignment and extending to a seaward radius of 1200m and beyond.

6. That the discharge of waste by the permit Holder shall not cause the receiving water quality limit, as prescribed in the Schedule 4 of the Regulations of the Water Resources Act, to be exceeded beyond the prescribed mixing zone.

7. The Permit Holder shall conduct the approved Environmental Monitoring Programme and shall report in writing to the Director of Water Resources on an annual basis or less as agreed by the Director of Water Resources and the Permit Holder.

8. The Permit Holder shall carry out additional monitoring of tailings disposal as may be reasonably required from time to time by the Director of Water Resources.

9. The Permit Holder shall not contaminate the marine water such that local populations of aquatic life are rendered unfit for human consumption.

10. The Permit Holder shall record the tonnes of raw tailing discharge and shall report to the Director of Water Resources on an annual basis.

11. This Permit is applicable to the proposals of the Approved Environmental Plans and any proposed changes to the Approved Environmental Plan in respect to tailings disposal will require prior notification to the Director of Water Resources.

12. The terms and conditions of the permit shall be reviewed as reasonably required by the Water Resources Board.

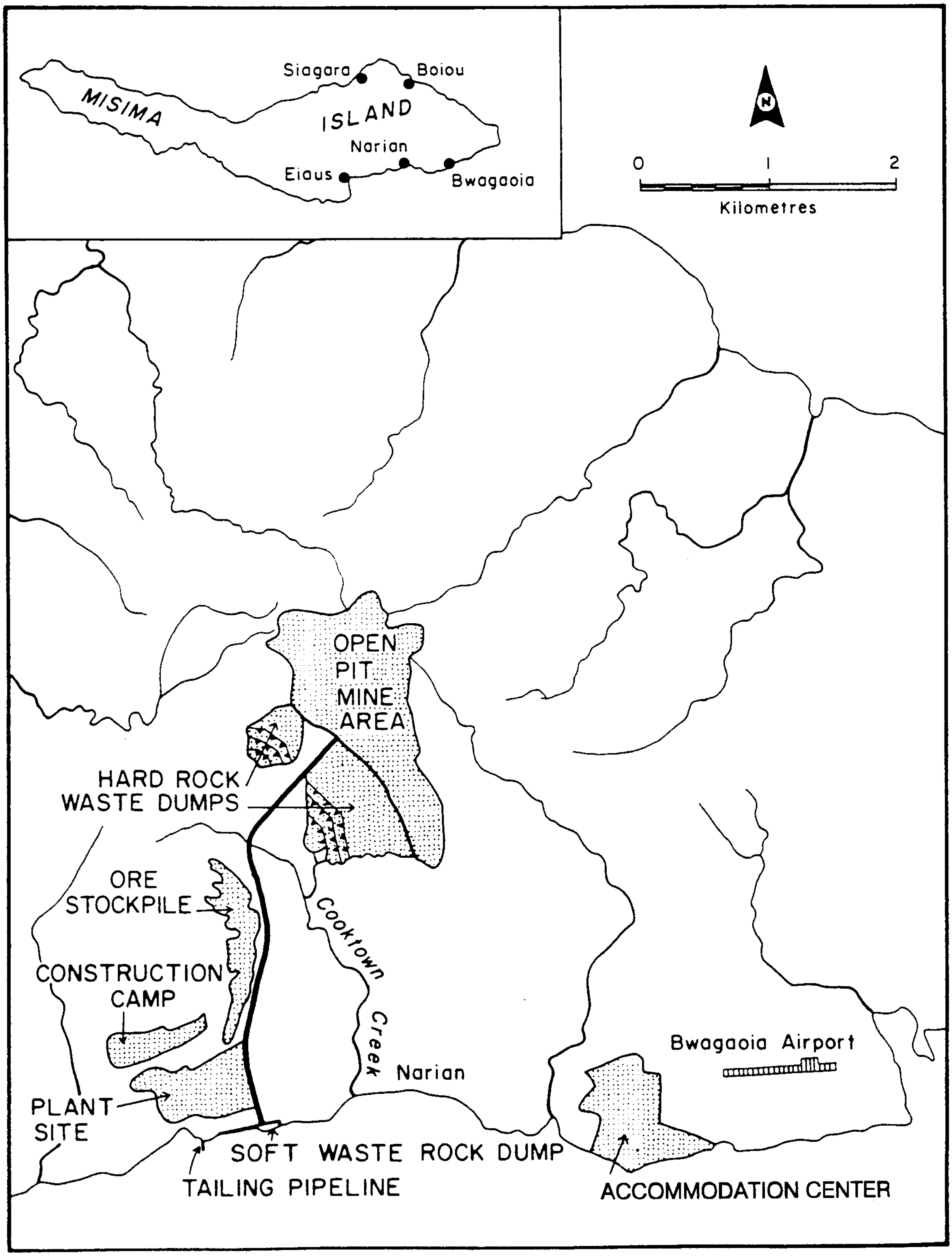

Figure 2.4 - Map Showing the Location of the Misima Mine, the Rock Waste Dumps and the Submarine Tailings Outfall (Reprinted and modified from Hughes, 1989).

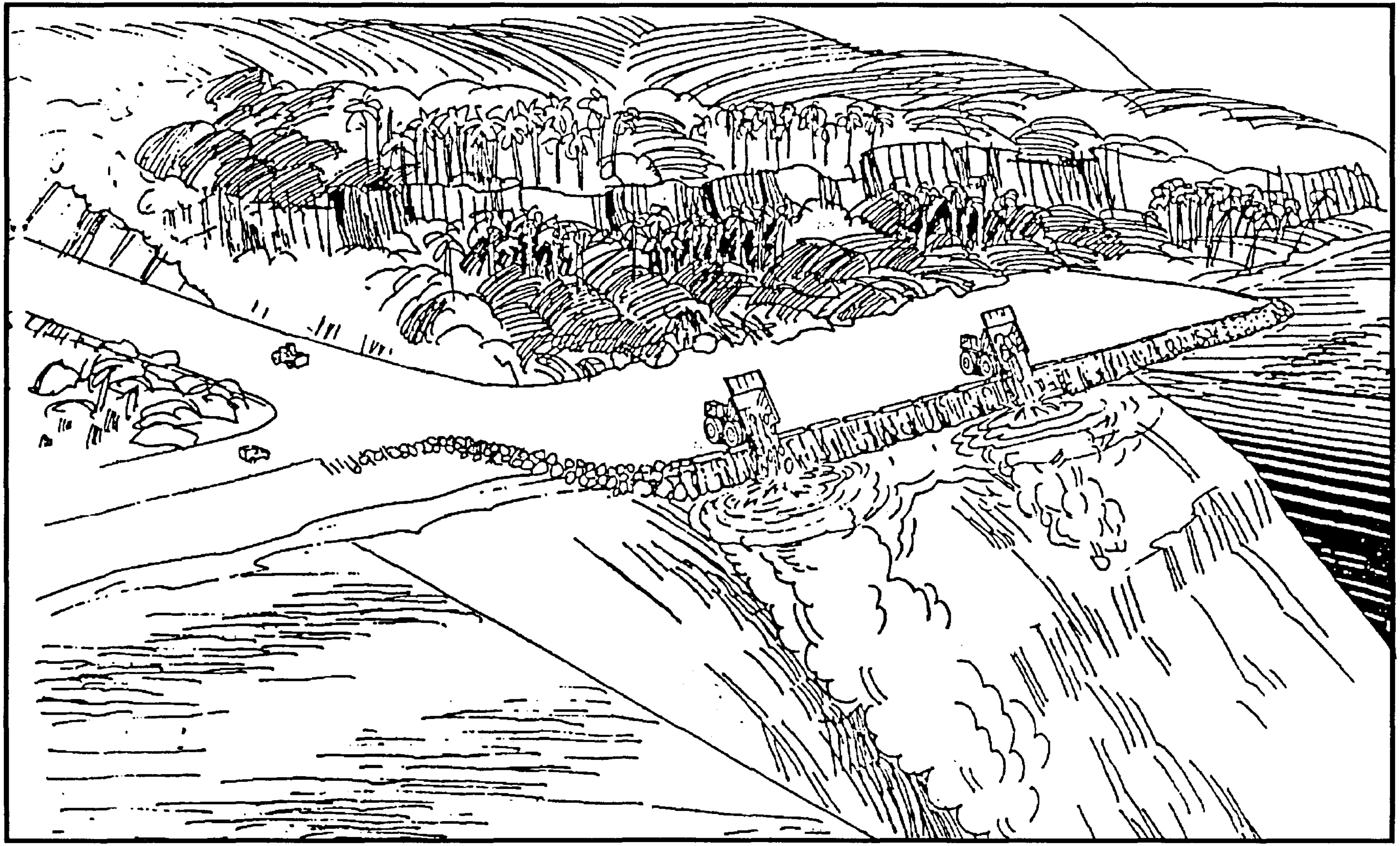

Figure 2.5 - Perspective of the Proposed Soft-rock Dump at Misima Mine (Reprinted and modified from NSR,1987).

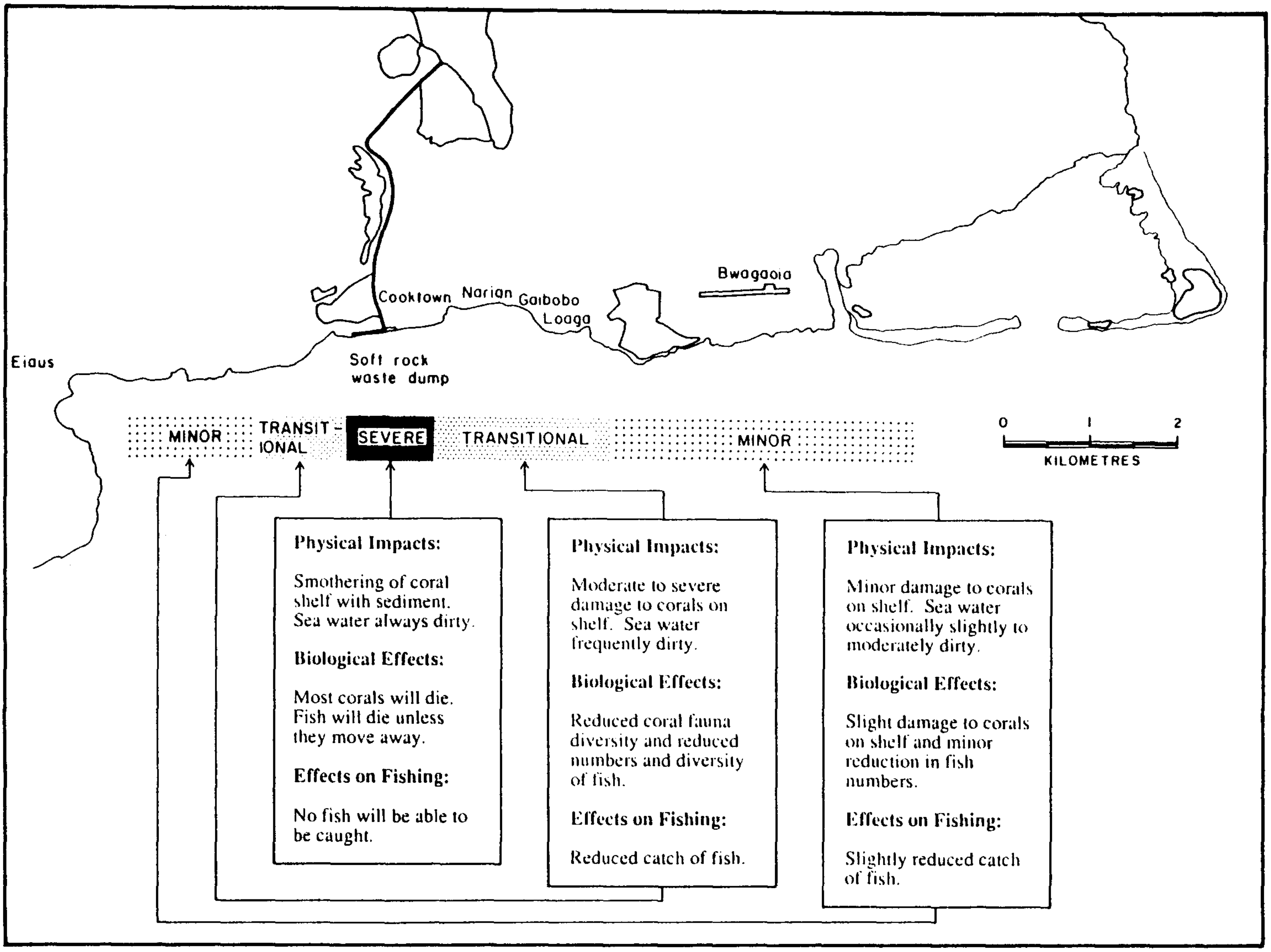

Figure 2.6 - Prediction of Shallow Water Marine Impact Arising from Dumping of Soft-rock Waste at Misima Mine (Reprinted and modified from Hughes, 1989).

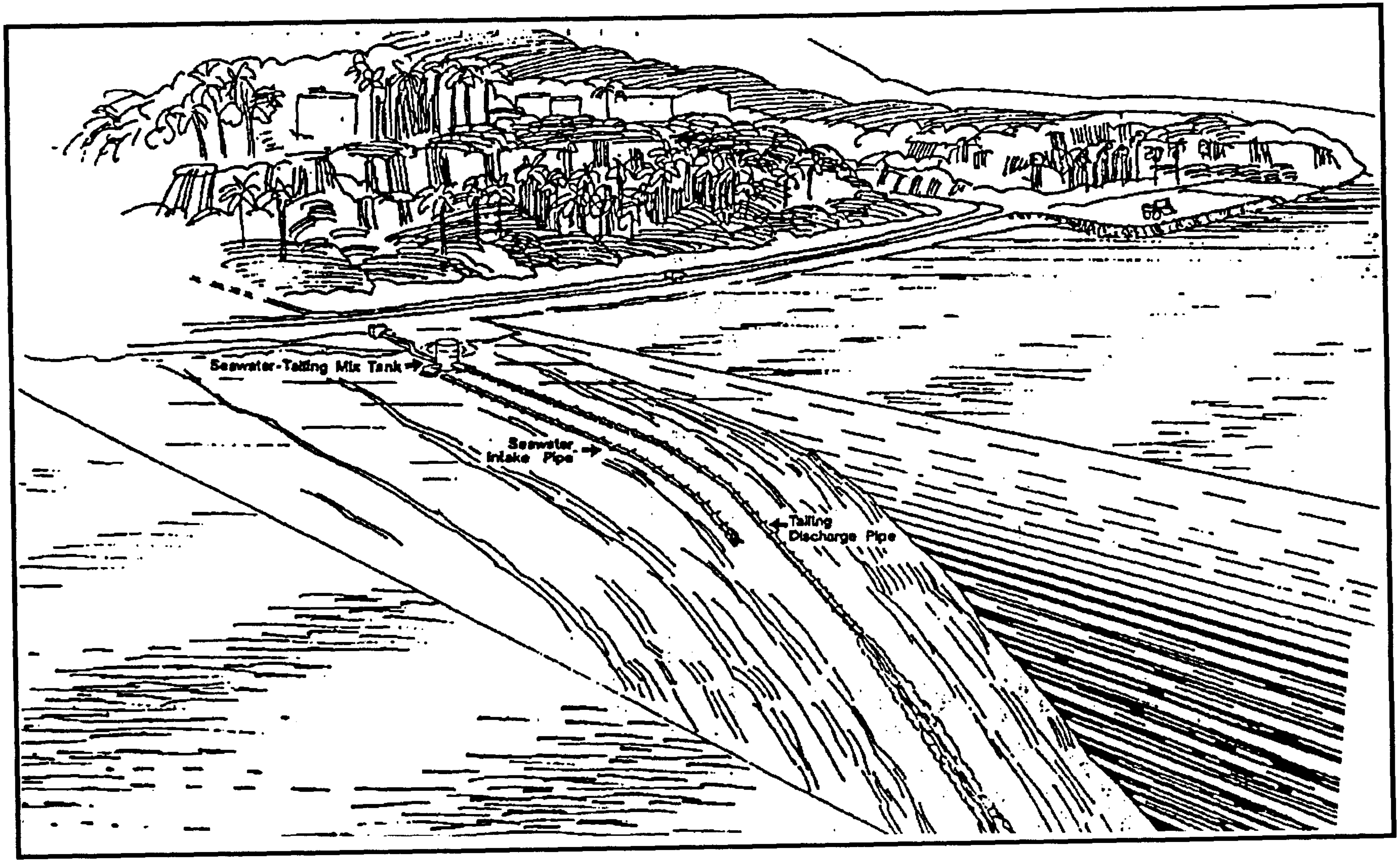

Figure 2.7 - Perspective of the Proposed STD System at Misma Mine (Reprinted and modified from NSR, 1987).

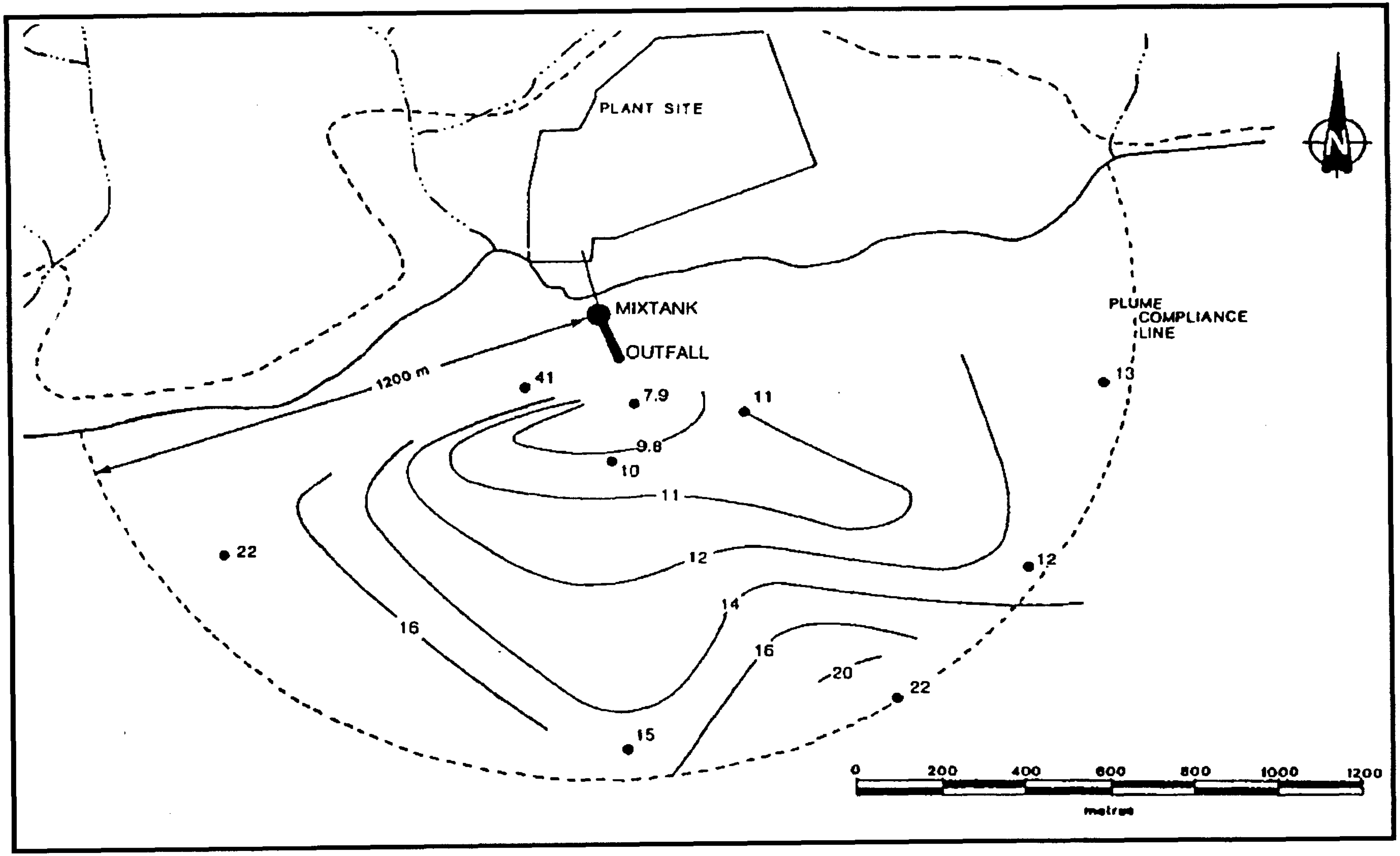

Figure 2.8 - Calculated Copper Dilution Levels within the Allowed Mixing Zone at Misima Mine (Reprinted and modified from Rescan, 1990).

to 22000:1 (Rescan, 1990). "All PNG receiving ocean water ambient standards for metals and cyanide were met before or at the boundary of the mixing zone" (Table 2.3). The profiles of suspended solids and the submersible observations demonstrated the presence of some turbidity fields, but all below the mixed layer depth.

2.6 The Environmental Situation

2.6.1 Bathymetry

Figure 2.9 shows an extended and consistent slope offshore near the mine out to 1100 meters depth. Fig. 2.2 shows deeper water further offshore with maximum trench depths around 1600 meters.

2.6.2 Tailings Deposition at Great Depth

There is little information on the fate of the discharged tailings after discharge, and presumably eventual deposition at several hundred meters depth. The marine monitoring program (see Section 2.6.4) is limited to assessing impact in shallow water. However the Compliance Validation surveys (Rescan, 1990) used a submersible to check (among other objectives) for the development of suspended turbidity fields, with 15 dives to a maximum depth of 253 m. Several such fields were seen at varying depths. The fields were also detected by light transmission profiles to the maximum profiled depth of 360 m. Thus there was either some secondary plume development from the tailings density current or the turbidity fields could have been from other mine-derived sediment sources such as the soft waste dumping or turbid run-off from disturbed land onshore.

The conventional wisdom about abyssal sediments is that natural deposition on abyssal plains is very slow (See Ch.1.3), e.g. 1 cm in hundreds of years (c/f 1 cm p.a. at the edges of the tailings beds at Island Copper Mine (Volume I). The conventional wisdom also considers the abyssal plains as a calm place, unaffected by near-surface oceanographic dynamics. In any one place abyssal plains support a low biodiversity fauna with low productivity, although there is considerable variation in faunas from place to place (Pentreath *et al.*, 1988) and other references in Ch. 1.4.

Extension of this conventional wisdom implies that the abyssally-deposited tailings will smother almost all organisms even at the edges of the tailings, and that recovery to a productive ecosystem will be very slow indeed. At Misima the social implications of this conventional wisdom was summarized by Hughes (1989). "The Misima people do not fish at such great depths and there is little potential for commercial deep water fishing."

The implications of the conventional wisdom may not be accurate in the real situation. Ch. 1.4 has been provided as a review of deep-sea biology in the context of potential environmental impact of abyssally-depositing anthropogenic turbidity currents. It is based partly on direct submersible observations of inert red mud discharges from aluminum smelters, and partly on recent biological information.

Table 2.3. PNG Trace Metal Receiving Ocean Standards and Maximum Measured Concentrations within the Permitted Mixing Zone for the Misima Mine (Rescan, 1990).

Metals		Max. Conc. Measured in 1,200 m Mixing Zone (mg/L)	PNG Receiving Ocean Standard (mg/L)
Arsenic	As	1.6	50
Cadmium	Cd	.36	1
Cobalt	Co	.26	-
Chromium	Cr	<1.0	-
Copper	Cu	1.24	30
Iron	Fe	33.3	1000
Lead	Pb	2.08	4
Manganese	Mn	46.0	-
Mercury	Hg	<0.05	0.2
Molybdenum	Mo	13.0	-
Silver	Ag	0.3	50
Zinc	Zn	6.8	5000

< = Less than.

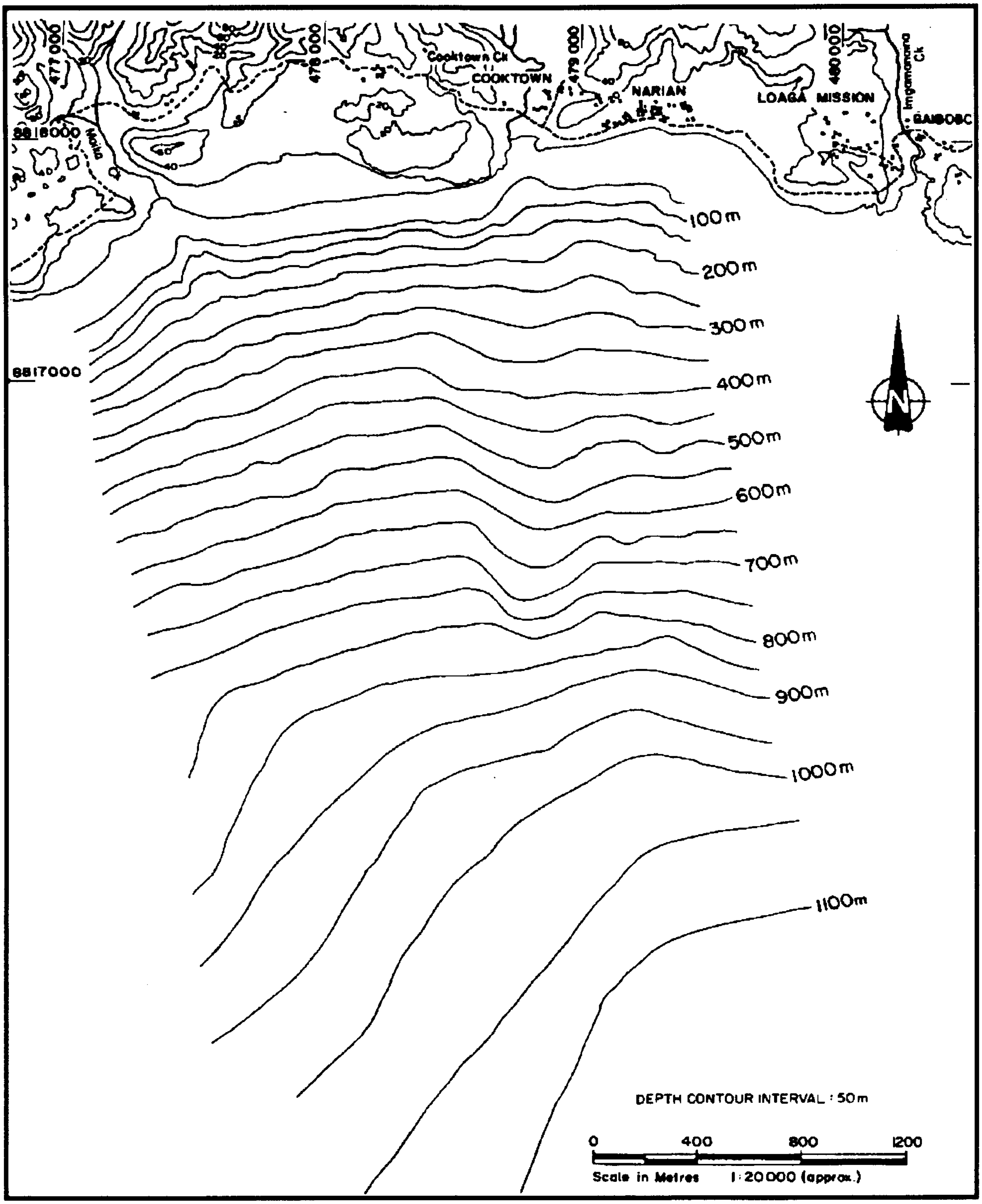

Figure 2.9 - Detailed Bathymetry in the Vicinity of the Milling Plant at Misima Mine (Reprinted and modified from NSR, 1986).

As shown in Ch. 1.4, it is now known that the deep sea ecosystem is not always a calm place and has potential to recover after natural catastrophes arising from (1) turbidity current flow, erosion and deposition, (2) massive slumps of perched turbidites (the risk of which however might be raised by Very Deep STD), and (3) abyssal *storms* generated by surface events. Nevertheless, in spite of much recent information there remain unknowns about the rate of recolonization, the impact of seasonal variation in food supply, and the food supply effect of *marine snow*, (*i.e.* bacterial aggregates on suspended particles such as tailing slimes?).

At this time we can conclude that the Very Deep STD at Misima has had some, but unmeasured, impact on the local abyssal fauna, but that recovery will occur drawing on the deep ecosystem potential for recolonization following natural slumps, turbidity current flow and abyssal *storms*.

2.6.3 Preliminary Environmental Information

The preliminary environmental information was presented in a substantial document by NSR (1987). Its predictions of marine environmental impact are summarized in Figure 2.6.

It was predicted that tailings plumes would not upwell to the surface if the discharge point was below the mixed layer depth. Data collected between November 1983 and January 1987 gave mean depths of 13-65 meters for this layer on the days of measurement.

Thus all shallow water impact would be derived from the shoreline dumping of soft waste rock, and flood plumes resulting from storm run-off. The impact would be severe one kilometre around the dump, and progressively less severe to a maximum of about 5 kilometers to the east of the dump. This was based on information about recovery from prior mining operations. Hughes (1989) provides an illustrative color photograph of a smaller turbidity plume derived from preliminary exploration.

The tailings outfall was designed with this information to discharge at a depth below the mixed layer so as to minimize the risk of tailing resuspension and upwelling.

The Compliance Validation Surveys (See Section 2.5) later confirmed that the discharge was being maintained below the surface mixed layer depth.

2.6.4 Monitoring

The monitoring programs proposed are shown in Tables 2.4 - 2.6. There was a substantial baseline program to establish existing conditions, by one-off and continuing surveys. An intensified monitoring program was applied during construction, especially to monitor sedimentation from the expected increased onland erosion and washout.

Monitoring proposed during mine operations include the Compliance Validations of the STD system, plus periodic routines. The major protective monitoring to check for tailings upwelling into shallow water is a monthly determination of mixed layer depth. If the mixed layer depth should ever drop below the outfall terminus, there is a proposed daily free cyanide monitoring.

Table 2.4. Proposed Environmental Baseline Survey Program at Misima. (Modified from NSR, 1986).

Component	Description	Frequency	Purpose
1. Cooktown Creek water quality	Water quality in Appendix 3 is considered adequate to describe baseline conditions.	-	Establish background water quality.
2. Cooktown Creek valley	Establish 5 permanent cross-sections (CS1-5) in Cooktown Creek valley mostly across the sago swamp.	Once off	Establish pre-construction stream-bed and valley floor levels against which future changes can be compared.
3. Rainfall	Continue collection of rainfall intensity data (SIAP weather station) in mine area.	Continuous monitoring	Establish long term frequency of rainfall intensities; continuous record will enable interpretation of floods.
4. Fringing coral reefs	Establish 10 permanent transects (T1-9) across fringing reefs on either side of soft waste dump, and at one control station (T10) on the north coast. Describe main reef structure by method of Dahl and undertake a phototransect of each.	Once off	Establish pre-construction status of fringing coral reefs against which future changes can be compared.
	Install one sampling tube assembly on transects (S1-20) and monitor sedimentation rates.	Monthly	Establish background sedimentation rates.
Contd.	Sample nearshore waters on each coral reef transect (T1-10), and Managuna Lagoon, and analyse for turbidity and total suspended solids, and store samples for possible future analyses.	Opportunistically during floods or strong winds, and once during dry weather or calm conditions.	Establish range in background levels of turbidity and total suspended solids.

Table 2.4. Proposed Environmental Baseline Survey Program at Misima (Modified from NSR, 1986) contd.

Component	Description	Frequency	Purpose
4. Contd.	Collect samples of common edible species of reef-attached and reef-associated fish and shellfish, and sample muscle and livers for metals (Cu, Ag, Pb, As, Zn, Hg and Cd).	Once off	Establish background metal concentrations in tissues of selected reef fish and shellfish.
5. Deep water fisheries	Determine by fishing the presence or not of a deep water fishery resource at Misima. If confirmed, sample the main species and sample muscle and livers for background metal content (Cu, Ag, Pb, As, Zn, Hg and Cd).	Once off	Confirm the existence of deep water fishery resource or otherwise. Establish background metal content of deep water fish.
6. Fisheries resource use	Determine existing subsistence consumption of fish and shellfish in g/person/day in selected south and north coast villages.	Once - Apr. to Nov. Once - Dec. to Mar.	Establish existing fishing practices and subsistence yields of marine food.
7. Upper ocean measurements	Continue existing program of thermocline surveys (TCA-D).	Monthly	Establish range in depths of mixed layer.

Table 2.5. Proposed Environmental Monitoring Program during construction at Misima (NSR, 1986).

Component	Description	Frequency	Purpose
1. Cooktown Creek valley	Survey valley cross sections (CS1-5).	Quarterly	Determine depth of sedimentation in Cooktown Creek valley.
	Monitor health of sago palms and other economically important plants, if surveyed sections change.	Quarterly	Determine effects of sedimentation on sago and other economically important plants.
	Construct observation bores to monitor ground water levels near infiltration gallery in Cooktown Creek.	Once off	To enable the determination of effects of draw down cone on sago swamp.
	Monitor ground water levels near infiltration gallery.	Monthly	Determine water table fluctuations.
2. Rainfall	Continue collection of rainfall intensity data (SIAP weather station) in mine area	Continuous recording	Establish long term frequency of rainfall intensities; continuous record will enable interpretation of flood events.
3. Nearshore turbidity	Intensive investigation of nearshore turbidity resulting from soft waste dumping: -monitor dumping rate (tonnage and soft waste type) -take frequent samples of nearshore waters for turbidity, suspended solids and particle size distribution. - record visual observations of turbid water movement.	Once off	Devise an accurate and efficient method of determining the frequency of turbid water conditions in the nearshore zone as a basis for compensation for loss of marine resources.
4. Marine sedimentation	Determine sedimentation rates in ocean using sedimentation tubes (S1-20).	Monthly	Compare with background the nearshore sedimentation rates from construction-derived sediment in flood plumes from creeks and turbid surface water plumes from soft waste dumping.

Contd.

Table 2.5. Proposed Environmental Monitoring Program during Construction at Misima (NSR, 1986) contd.

Component	Description	Frequency	Purpose
5. Fringing coral reefs	Survey permanent reef transects (T1-10) and assess construction-derived sedimentation impacts.	Once off at end of construction.	Determine sedimentation and turbidity effects on coral fauna and reef fish.
6. Upper ocean measurements	Continue existing program of thermocline surveys. (TCA-D).	Monthly	Establish range in depths of mixed layer.

Table 2.6. Proposed Environmental Monitoring Program during Operations at Misima (NSR, 1986).

Component	Description	Frequency	Purpose
1. Cooktown Creek valley	Survey valley cross sections (CS1-5).	6-monthly	Determine depth of sedimentation in Cooktown Creek valley.
	Monitor health of sago palms and other economically important plants, if surveyed sections change.	6-monthly	Determine effects of sedimentation on sago and other economically important plants.
	Monitor ground water levels near infiltration gallery.	Monthly.	Determine water table fluctuations.
2. Mill processing solutions	Routine sampling of all mill solutions will be carried out in accordance with good metallurgical practice.	Intermittently.	Process control and negative feedback. Determine tailing liquor quality prior to admixing with seawater in the mix tank..
3. Validation of tailing dilution after discharge	Intensive investigation of tailing behaviour after discharge and measurement of actual dilutions over a range of oceanographic conditions: - determine pertinent tailing characteristics prior to discharge. -measure upper ocean temperature, salinity and density profiles. -measure ocean currents and directions at depth. -Attempt to determine the areal extent and depth profile of the subsurface plumes using recording transmissometer. It is expected that these will be masked to an unknown extent by subsurface turbidity from soft waste dumping.	Once off, to be undertaken as soon as the processing plant achieves normal operation.	Validate the Environmental Plan's predicted dilutions of tailing contaminants and the applicability of the adopted mixing zone. Confirm that the tailing remain at depth in the ocean or otherwise. Determine the free cyanide concentration at edge of the mixing zone.

Contd.

Table 2.6. Proposed Environmental Monitoring Program during Operations at Misima (NSR, 1986) contd.

Component	Description	Frequency	Purpose
	Sample tailing plume at depth in the ocean at around the discharge point and at distances from the discharge. - Analyse samples for free cyanide (HCN) by macrodiffusion method.		
4. Depth of mixed layer	Continue monitoring of mixed layer depth by thermistor string and telemetry to shore based receiver.	Monthly.	To determine whenever mixed layer depth is deeper than the tailing discharge.
5. Sampling for CN in mixed layer	Whenever mixed layer is deeper than the tailing discharge undertake sampling of the mixed layer water column for free cyanide.	Daily until mixed layer rises above discharge.	Determine concentrations of free cyanide in upper water layers.
6. Soft waste disposal	Determination of extent of turbid water in nearshore zone by method devised during construction monitoring.	To be determined.	Determine compensation for loss of marine resources.
7. Hard waste rock dumps	Sampling and analysis of dump leachate water quality.	Quarterly	Determine whether acid leachate is produced.
8. Fringing coral reefs	Sampling of 10 permanent coral reef transects (T1-10) using method of Dahl and continuing phototransects. Assess long term changes in reef ecology and structure.	Annually	Biosurveillance and long-term monitoring of sedimentation and turbidity effects on reef structure.
	Determine sedimentation rates on coral reef transects (S1-20) using established sedimentation tube sampling assemblies.	Monthly	Relate sedimentation rates to sedimentation induced changes in reef ecology.

At the time of writing, we do not know details of the monitoring program, nor are results available to us.

2.7 Conclusions

The STD system at the Misima Mine was developed and installed using contemporary engineering and environmental knowledge and standards. Two Compliance Validation surveys showed that the system met its design criteria. The criteria were to achieve dilutions of 10,000:1, and to meet trace metal ambient seawater standards, at the edge of a mixing zone 1200 meters distant from the outfall location. Some deep turbidity fields were detected below the seawater mixed layer depth, but there were no indications that these were upwelling into shallow water.

3.0 THE BLACK ANGEL LEAD-ZINC MINE (GREENLAND)

3.1 Introduction

The Black Angel lead-zinc mine is located at Marmorilik within a complex of fjords in mid-western Greenland (Figure 3.1). It is about 50 km in from the wide Umanak Fjord opening to the west coast.

Black Angel is an important case history as the STD system adopted did not prevent contamination of the receiving area. This arose through a complex of causes, which are well documented. The case thus demonstrates some mining and environmental parameters which must be accommodated within the design of an STD system, and in operation of the milling system.

The mine was unusual in that the milling process was based on seawater, not freshwater.

The case is also a little confusing in that local Greenland fjord names are polysyllabic, and the versions used in the documents have changed over the years. Affarlikassa was initially known as Agfardlikavsa and Qaamarujuk as Qaumarujuk. We follow the common practice in the later literature of referring to them as *A* and *Q* fjords (Figure 3.1).

The mine portal was located 600 meters above the *A* fjord water surface. The name derives from the angelic appearance an exposed contorted band of argillaceous pelite associated with a mineralized outcrop visible on the steep face of Black Angel Mountain. The outcrop was easily visible from the sea and had long been a landmark for sea captains. The Danish government granted a mining concession to prospectors Anderson and Watts in 1962. In 1963 a syndicate was formed among Cominco, Westfield Minerals, Anderson and Watt; Greenex A/S was incorporated in 1965 to explore the property. Using Swiss mountain climbers a portal was established on the cliff face and an adit driven into the ore body. Two aerial cableways were built to transport men and materials from the plant site situated more than $1^1/_2$ kilometers away and near sea level across the fjord at Maarmorilik.

The mining concession was granted in 1971, and by 1972 had outlined a major lead-zinc orebody. The mine was by then known as Vestgron with Cominco owning a 61.5% interest. A closed-down phosphate concentrator in Montana was dismantled and shipped to Greenland to assist in "fast-tracking" mine start-up. With the fjord iced-in all winter and only a short summer shipping season (June-November) available, a plant start-up on August 11, 1973 was a remarkable achievement. Black Angel is generally considered to have been the first modern mine in the Western Hemisphere to have been brought into production in truly arctic conditions.

With the absence of suitable land disposal sites close by the mine, the Danish government gave approval by mid-1972 for disposal of the tailings *underwater*. In a general technical description of the project in August 1974, Eric Mikkelborg, Associate Editor of the Canadian Mining Journal said "...there is no trace of tailings to be seen anywhere. Of course the obvious place for them is in the fjord and thats where they go....Even at the shoreline the fjord is well over 200 ft. deep and the tailings are just swallowed up."

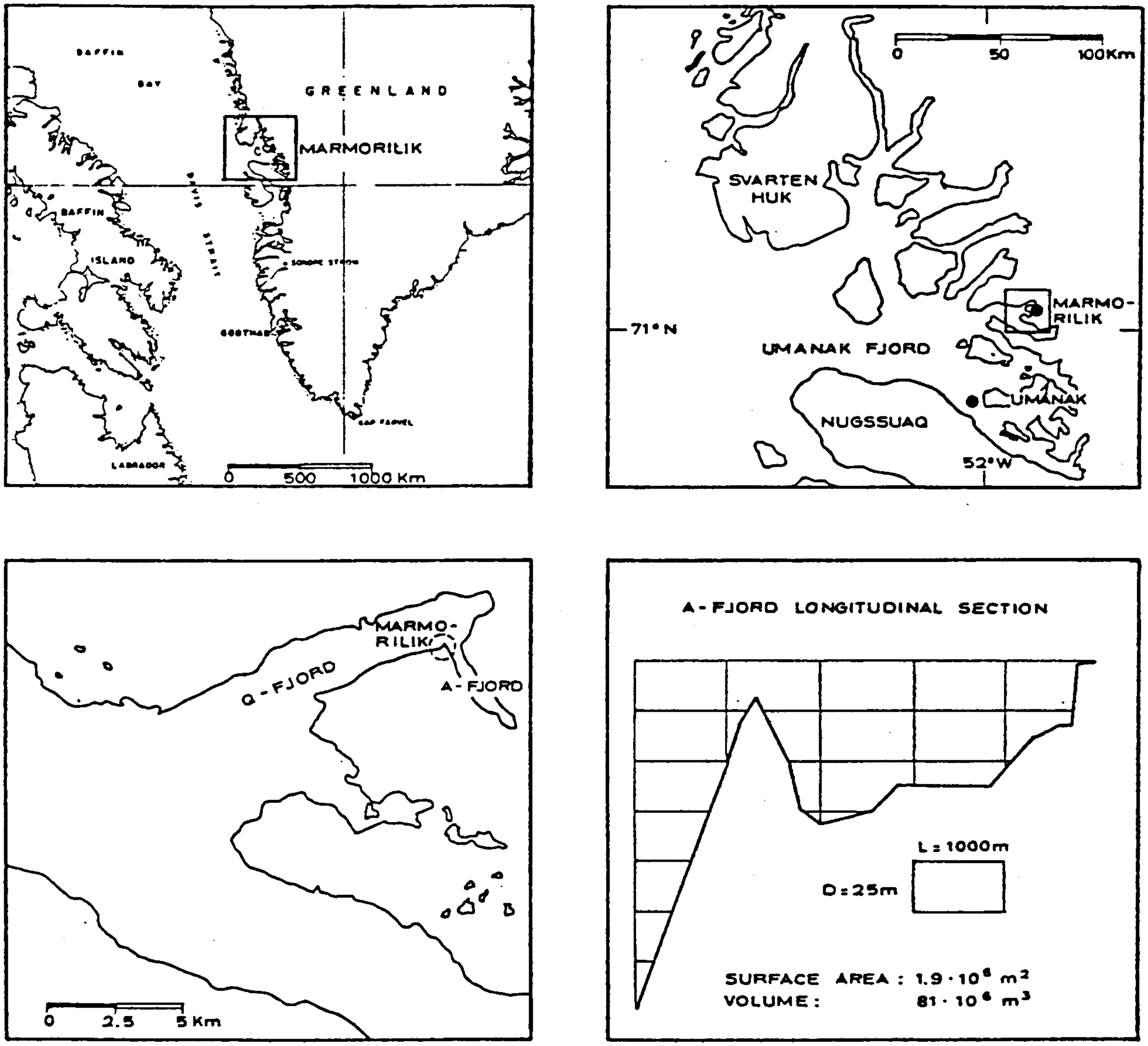

Figure 3.1 - Location and Longitudinal Section of the Tailings Disposal Site at Black Angel mine (Reprinted and modified from Nielsen and Hansen, 1980).

As it turned out these statements depicted a far too simplistic evaluation. By 1974 Danish scientists found significant increases in dissolved lead and zinc in the sea water column near the bottom of the *A* fjord, and a major environmental program was underway. The mine continued to operate (with chemical abatement technologies applied) until 1990. Monitoring has continued by Danish environmental scientists since then.

3.2 Composition of the Orebody

The Black Angel ore is a massive sulphide orebody with sulphides comprised mainly of pyrite (FeS_2), sphalerite (ZnS) and galena (PbS). These sulphides are hosted in a light colored marble with tremolite and talc-bearing marble. The host rocks in the orebody have been age dated at ~1700 million years. Ore reserves in 1974 were 4,440,000 metric tonnes grading 14.9% zinc, 5.0% lead and 1.0 oz of silver per tonne of ore. Pyrite content of the ore ran approximately 20%. The main Black Angel ore zone was an approximately flat-lying lenticular body ca. 600 meters long and 400 meters wide bulging out to a thickness of ca 20 meters in the middle.

3.3 Mining and Mineral Processing

The Black Angel ore body was mined using open stope, room and pillar underground mining and trackless (rubber tired) equipment. Figure 3.2 shows a cross section through Black Angel Mountain plus a plan view and a typical stope mining layout. Ore in permafrost was typically drilled (using salt water drilling fluids to prevent freezing) and blasted (using ammonium nitrate plus fuel oil) to produce a daily output of ~2150 tonnes of ore plus 180 tonnes of waste rock per day. Initially at least, the waste was dumped out of the portal to run down the side of the mountain and stack on the side of the fjord. The ore was transported via trains, underground and then, after crushing to -2 cm in an underground crusher station, sent via a cable car skip system to the mill near sea level. The 11 tonne skips travelled at 4, 7 or 10 m. per sec. along the 1500 m. span to the mill. The skip guide cables were 6.3 cm diameter and anchored solidly in rock at both top and bottom ends. A lighter central travelling cable was used to drive each skip. Ore was dumped into a 4000 tonne live storage bin at the concentrator.

The concentrator used conventional rod mill-ball mill grinding plus hydrocyclone classification to reduce the ore to 55% - 200 mesh (74 microns) to liberate the lead and zinc valuable minerals. This was followed by froth flotation to produce separate lead and zinc concentrates plus a tailing for submarine disposal. Figure 3.3 shows a two page pictorial-type process flow diagram for the concentrator.

In order to appreciate the tailing characteristics it is important to understand the essential features of the flotation processes. First, this concentrator was unusual in that the flotation circuit used sea water instead of fresh water. Second, it is important to understand that in order to make an efficient lead (galena)-zinc (sphalerite) separation, in addition to Xanthate (n-amyl dithiocarbonate) collector and Dowfroth (propylene-oxide) frother, sodium cyanide and zinc sulphate were added in the lead flotation circuit. These were added to depress (prevent flotation of) the sphalerite. After the galena was floated off then copper sulphate was added to *activate* the sphalerite and then a zinc concentrate was floated from the pyrite and silicate tailing.

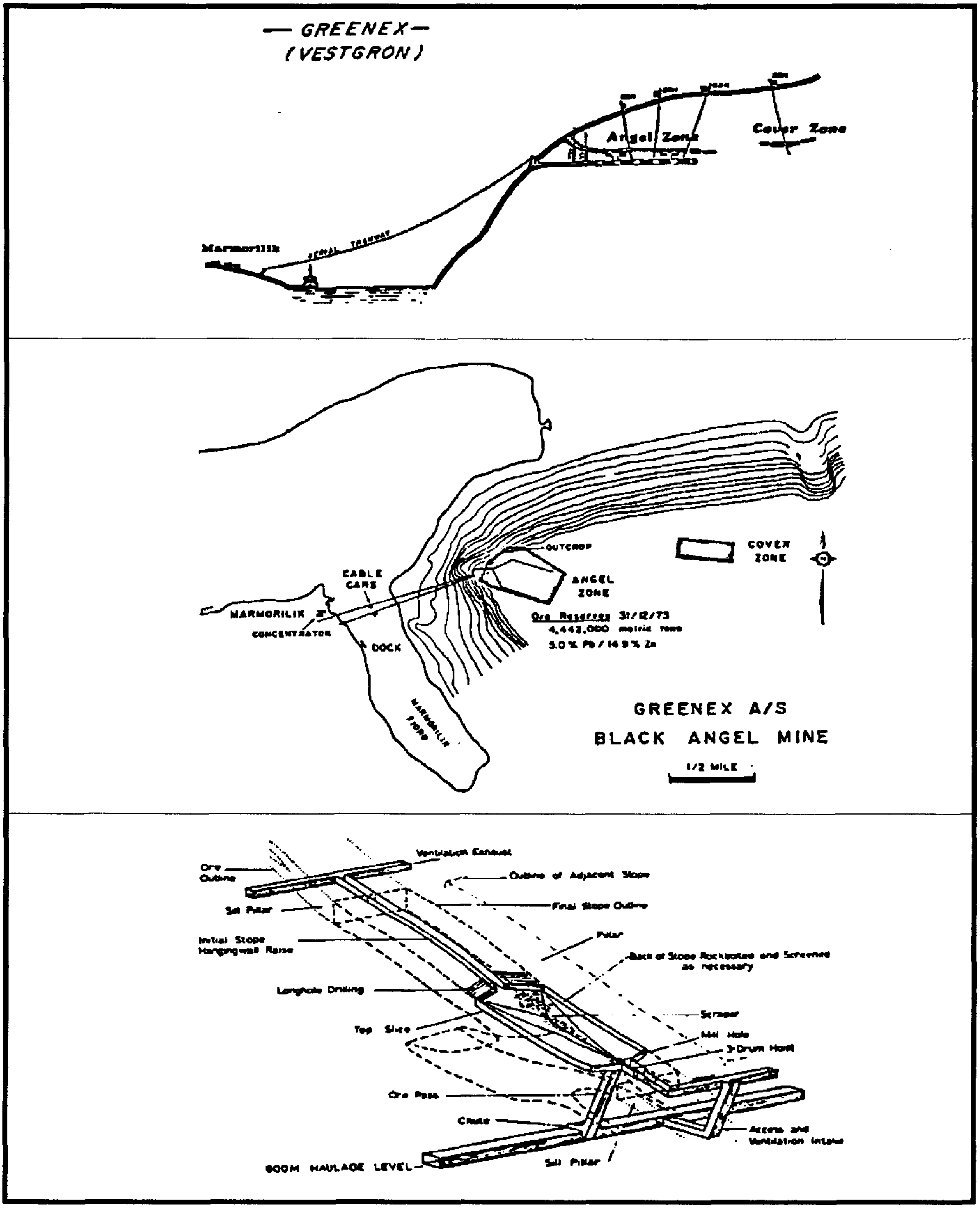

Figure 3.2 - Details of Mine Location and Mine Plan for the Black Angel Mine (Reprinted and modified from Mikkelborg, 1974).

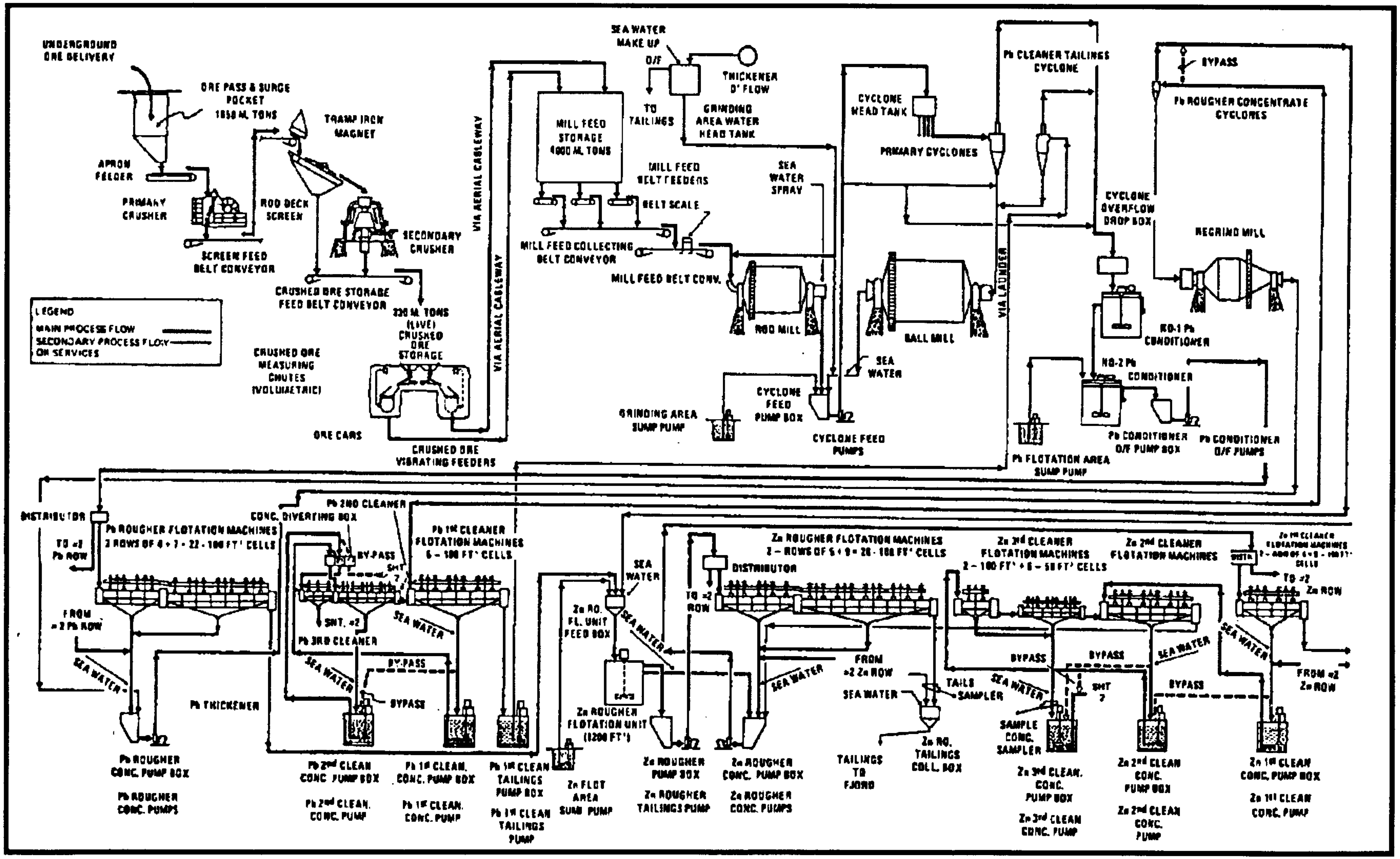

Figure 3.3 - Process Flow Diagrams for the Black Angel Mine (Reprinted and modified from Mikkelborg, 1974).

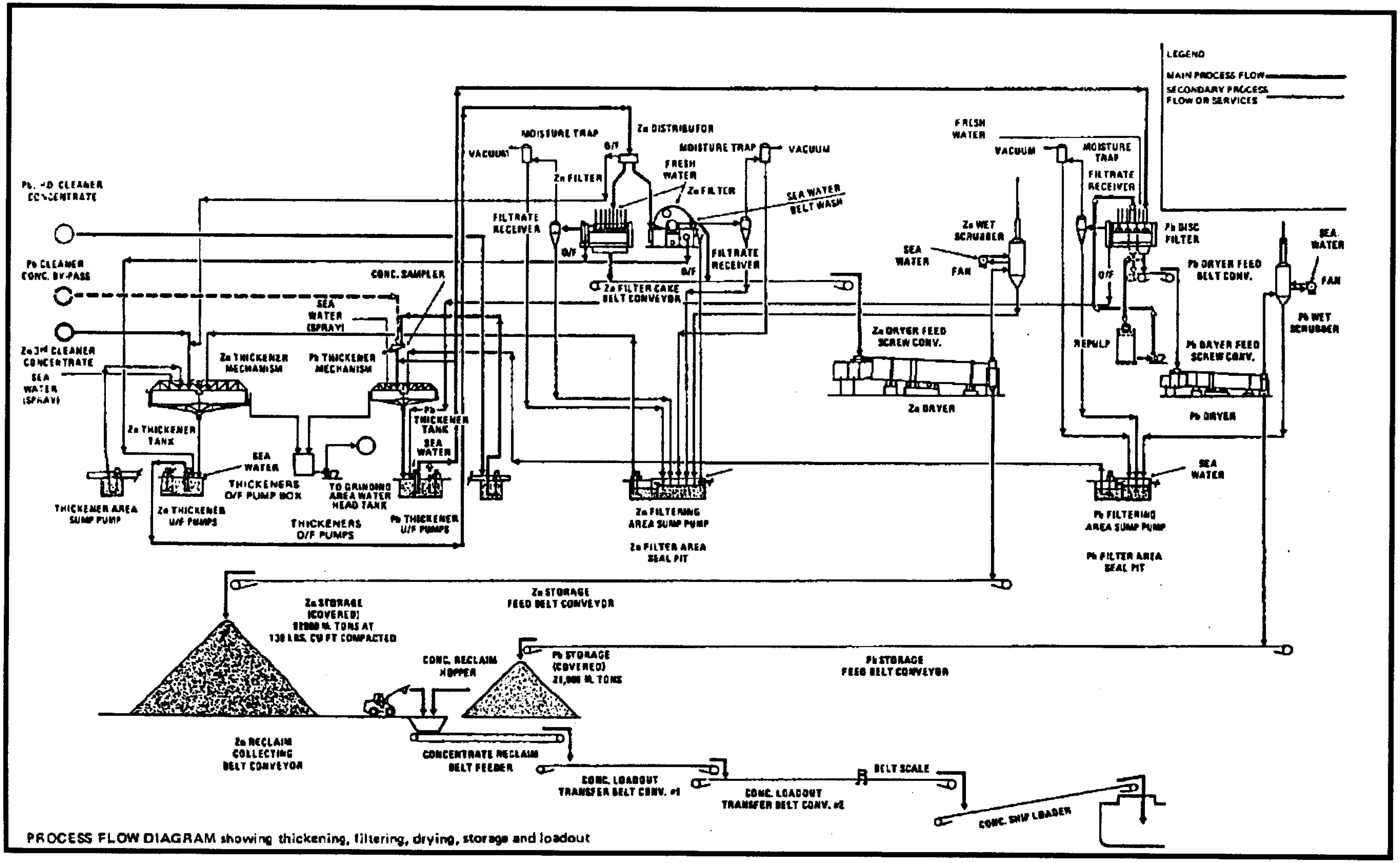

Figure 3.3 - Process Flow Diagrams for the Black Angel Mine (Reprinted and modified from Mikkelborg, 1974) continued.

Initially in the lead circuit, sodium cyanide was added at a level of ~107 g/T and zinc sulphate at 290 g/T of ore feed. Copper sulphate was added to the zinc circuit at 580 g/Tonne. At 2100 Tonnes per day ore feed rate this would amount to:

225 kg NaCN plus
420 kg $ZnSO_4$ plus
1220 kg $CuSO_4$ added

each day of mill operation. Some of each of these reagents would be expected to report to the tailings, dissolved in the liquid phase.

3.4 Preliminary Tailings and Environmental Information

3.4.1 Early Waste Discharge Characteristics

In a report published in January 1979 (Kuit, 1979) Cominco Technical Research reported that the Black Angel tailing, over the production period of April 1-19, 1978 averaged:

45.1 g/T Available soluble lead
and 3512 g/T Available soluble zinc.

These were equivalent to totals of 61 and 420 kg/day respectively at a tailing discharge rate of 1350 T/day. Over this sample period the tailings solids assayed on average of 0.45% Pb and 0.90% Zn. This was equivalent to a discharge of:

6075 kg Pb solid and
12150 kg Zn solid each day.

Analyses indicated that the available soluble metals (Pb & Zn) in the tailings bore no relationship to the total Pb and Zn lost as solid galena and sphalerite particulate. Thus improving metallurgical efficiencies would not necessarily reduce the available soluble metal levels.

Lab simulations indicated that using *antifreeze* drilling brine in the mining operation contributed significantly to the available soluble lead in the mill tailing. In contrast, the zinc sulphate flotation depressant reagent appeared to be a major source of the available soluble zinc in the tailing.

In 1979, Kuit of Cominco Research recommended that Greenex A/S evaluate (i) chemical treatment of the tailing with $FeCl_3$ and $Al_2(SO_4)_3$; (ii) abandoning $CaCl_2$ and seawater brine drilling fluids and (iii) replacing $ZnSO_4$ as a ZnS depressant and minimizing use of $CuSO_4$ as a ZnS activator. (See Section 3.6.2 following)

3.4.2 Discharge Controls and Preliminary Environmental Information

Danish authorities granted approval for the Black Angel Mine to dispose of tailings *underwater* in July, 1972.

Greenex further committed (Wadey, 1972) that prior to start up, consultants would carry out an oceanographic survey in the vicinity of the mine to determine:

- basic temperature-salinity profile to 200 meters
- particle numbers and size distributions
- soundings for both *A* and *Q* fjords for ~1.5 km
- predictions on tailings depositions in the inlets.

Greenex also predicted characteristics of the tailings to be discharged:

Ore milling rate 1650 MT/day
Reagents used:

xanthate	-	collector	-	0.15 kg/MT
MIBC	-	frother	-	0.02 "
NaCN	-	depressant	-	0.20 "
$CuSO_4$	-	activator	-	1.0 "
Lime	-	pH regulator	-	1.27 "
$ZnSO_4$	-	depressant	-	0.32 "

Tailings were expected to analyse:

Pb	0.18%
Zn	0.32%
Fe	19.1%
Cu	0.037%
Cd	0.002%
As	0.013%
Ni	7 ppm
Co	<5 ppm
Hg	0.75 ppm
Sb	0.003%

The tailings were expected to be 61.4% - 200 mesh.

Water used in the mill was expected to be:

Sea water - grinding - 900 1/min
Sea water - flotation - 1300 1/min

Fresh water - filter cake wash - 85 1/min

Total 2285 1/min

Tailing was expected to leave the mill at 24.8% solids (slurry S.G = 1.215) at in a pH range of 8-8.5 and at a temperature of 4.0-18°C.

Potential toxic constituents were expected to be:

Pb total	500 mg/l
Pb diss	0.12 "
Zn total	886 "
Zn diss	0.59 "
Cu diss	0.12 "
CN diss	2.0 "
Fe total	52,500 "
Fe diss	2 "
Xanthate diss	4.0 "

Cominco contracted Drs J.L.Littlepage and D.V. Ellis (1972) of the University of Victoria to collect oceanographic data during the period July 29, 1972 to August 4, 1972. These data were to assist in locating sea water intake and tailings and domestic sewage lines to minimize environmental damage. Danish scientists Bondam and Asmund (1973) monitored background or natural levels and conditions in these same inlets prior to mining operations during two periods, August 24 - September 1, 1972 and in July 1973. Mr. Arne Bohn and other scientists of B.C. Research (1972-3) also undertook preliminary studies of environmental parameters.

Littlepage and Ellis (1972) recommended that the tailing outfall should discharge at 30 meters depth to *Q* fjord at a gully located immediately west of *A* fjord sill (See Figure 3.1). They recommended that the sea water intake be in *A* fjord and a separate domestic sewage outfall line in *Q* fjord. Concern was expressed about the freshwater sewage contributing buoyancy in seawater, hence the recommendation that sewage not utilize the tailing outfall. The gully that the tailings would flow and subside into was approximately 100 meters deep off the proposed outfall location. They rejected *A* fjord as the discharge site due to the expected typical winter under-ice destratification of the water column. Any dissolved contaminants would then disperse throughout the water column and flow out from *A* to *Q* fjord at the surface the following summer.

Danish regulators favored tailings discharge to *A* fjord for reasons summarized by Asmund. "...less dissemination of tailings solid, and therefore less contact with sea water and dissolved oxygen, lower temperatures, more control of where the tailings end." (Personal communication, 1993)

Asmund also added:

> *Q* fjord is rich in fish whereas *A* fjord is not. The natural sedimentation in *A* fjord is higher than in *Q* fjord, thus the tailings in *A* fjord will be naturally covered faster than tailings in *Q* fjord. The bottom water of *A* fjord is actually stagnant for most of the year.

This meant that saturation concentrations could build up and also a pH elevation in the bottom water of *A* fjord could be obtained.

Winter homogenizing of *Q* fjord can go down to 70 m. Thus, in order to achieve any benefit of discharging the tailings to *Q* fjord one had to build the discharge system to a depth of more than 70 meters.

3.5 The Tailing Disposal System

From the concentrator, tailings were pumped with a 25 x 20 cm centrifugal pump through a 709m long x 20cm diameter wood stave pipeline to the fjord. There they were discharged 33m below the surface as shown in Figure 3.4.

The submarine discharge point is near the upper end of a gentle slope leading down an axial trench to an ultimate depth in *A* fjord of ~80 meters. Note that this system does not have a preliminary sea water mix tank and that *A* fjord is relatively shallow. Since the concentrator operated with sea water, not fresh water, a sea water mix tank would have achieved little purpose - other than possibly temperature equalization.

3.6 The Environmental Situation

As mentioned in section 3.4.2 preliminary environmental-oceanographic surveys were conducted by Littlepage-Ellis and Bondam-Asmund. Bohn and other B.C. Research personnel also conducted the first of several surveys and analyses for Cominco over the period 1972 to 1983.

3.6.1 Bathymetry and Oceanography

Figure 3.4 shows that the submarine discharge point for Greenex tailings was at a ~33 meter depth in *A* fjord. This fjord has a maximum depth of ~80m and a length of just under 4 kms. A 24m sill separates *A* fjord from *Q* fjord. Figure 3.4 also shows water depths in both *A* and *Q* fjords. Volumes of water contained within various depth intervals in *A* fjord is shown in Figure 3.5.

Both *A* and *Q* fjords are strongly stratified in summer as a result of fresh water runoff. In fall and winter, sea ice growth and density currents of heavy salt water from *Q* fjord over the sill to *A* fjord results in homogenizing of the water column in *A* fjord, and hence dispersal of dissolved contaminants. Cross fjord resonance processes are also proposed to contribute to exchanges between *A* and *Q* fjords (Moller, 1984).

3.6.2 Environmental Monitoring and Derived Process Changes

Full production of the Black Angel Mine commenced in October 1973. Chemical monitoring of tailings and seawater is summarized in Tables 3.1 and 3.2, and an overview of the environmental data derived in Table 3.3. It should be noted that the state of the art for making reliable low level trace metal analyses has substantially improved during the last two decades, and that the early results may not be as reliable as those later.

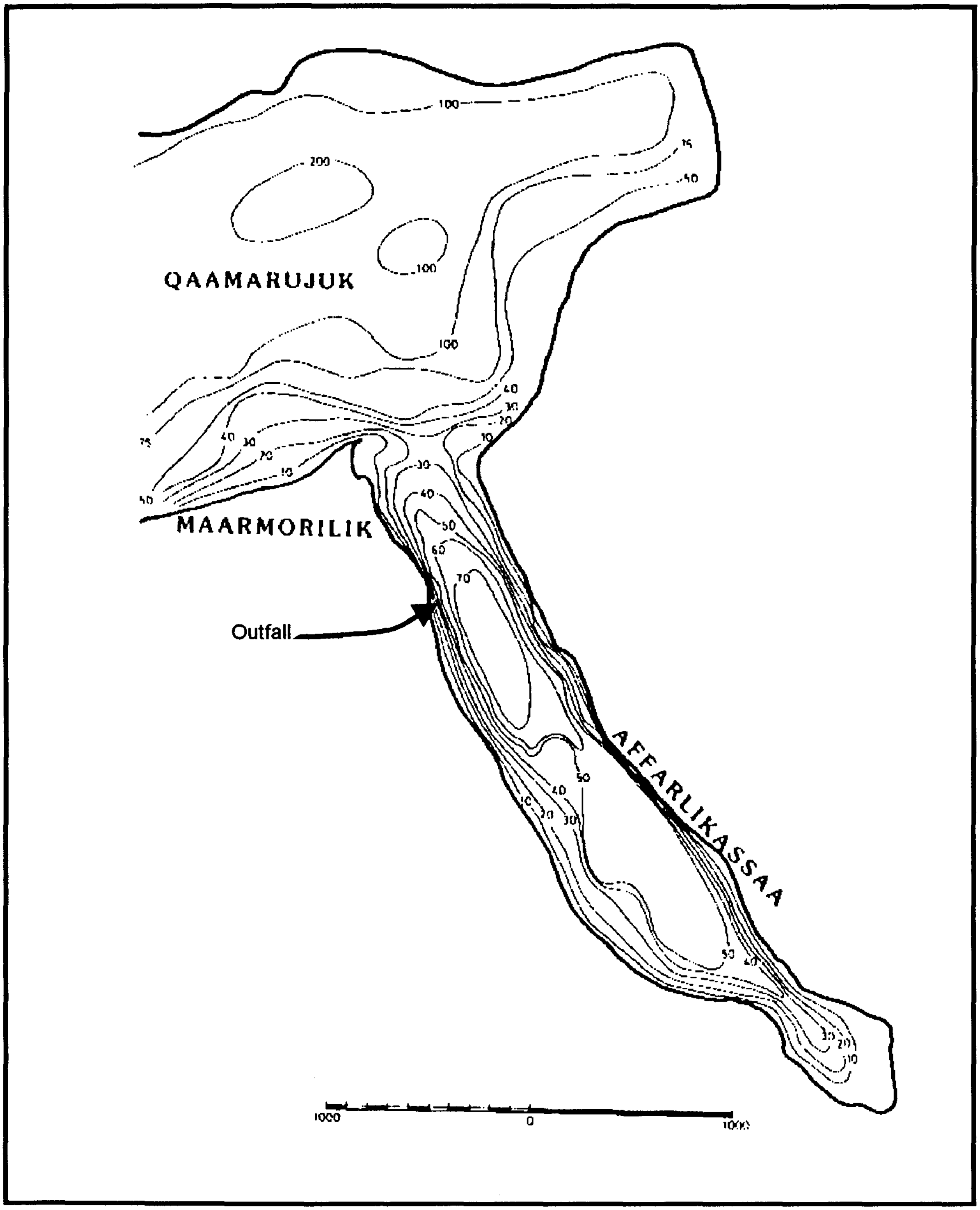

Figure 3.4 - Bathymetry of "A" Fjord near the Black Angel Mine (Reprinted and modified from Moller, 1984).

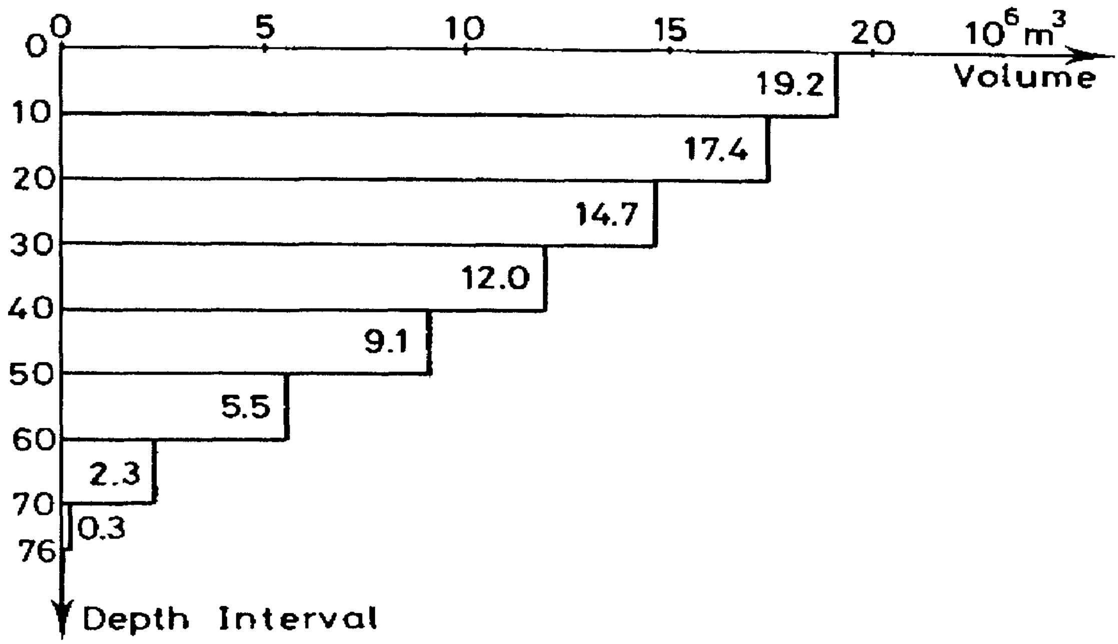

Figure 3.5 - Fjord Volumes between Contour Depths for "A" Fjord near the Black Angel Mine (Reprinted and modified from Moller, 1984).

Table 3.1 Tailings Characteristics; Predictions and Actual Values at the Black Angel Mine (Collated from various sources). All values in mg/kg.

	Expected:	Actual:		
		1979	1984	1989
Pb	1800	3100	1500	1800
Zn	3200	7500	2600	2400
Fe	191000	198000	151000	142800
Cu	370	176	113	110
Cd	20	45	17	21
As	130	77	71	95
Ni	7	-	-	-
Co	<5	-	-	-
Hg	0.75	1.3	0.36	0.36
Sb	30	-	-	-

Table 3.2. Mean Concentrations of Heavy Metals in "A" and "Q" Fjords near the Black Angel Mine (After Bondam and Asmund, 1973).

		Zn		Pb		Cu		Fe	Ni	Hg	Ag	As	Se
		sus-pended	dis-solved	sus-pended	dis-solved	sus-pended	dis-solved	dis-solved	dis-solved	sus-pended	dis-solved	dis-solved	sus-pended
Agfardlikavsa													
2m depth	no. of samples	4	1	4	2	4	2	3	3	4	2	2	4
	ave. conc. ppb	1.0	77	4.5	13	2.0	71	3.2	23	3.0	0.5	1.4	2.5
	range ppb	0.5-1.5	-	2.5-7	0.5-25	0.5-4	7-135	0-4.3	0-70	2.5-4	0.3-0.6	0.7-2.0	1.5-3.5
20m depth & 5m above bottom	no. of samples	8	7	8	8	8	8	8	8	8	8	5	8
	ave. conc. ppb	1.5	57	7.0	19	3.5	40	2.6	13	4.5	0.6	1.9	3.0
	range ppb	0.5-3.5	3.3-87	3-16	3-58	1-8	3-20	0-5.9	0-55	2-10	0.1-1.1	0.6-3.3	1.6
Qaumarujuk													
2m depth	no. of samples	8	8	7	8	8	7	7	8	7	8	8	7
	ave. conc. ppb	1.0	51	4.5	7	3.0	14	2.2	1.2	3	0.6	1.8	1.8
	range ppb	0-4	23-91	1-8	1-16	0-11	1-35	0-5.9	0-4.1	1-4	0-1.6	0.5-2.7	0-4
50m depth & 5m above bottom	no. of samples	15	13	15	15	14	16	15	16	15	16	14	15
	ave. conc. ppb	1.0	56	5.0	6.5	3.5	12	2.9	1.5	3.5	0.8	1.6	2
	range ppb	0-3	31-105	1-14	1-17	1-8	2-25	0.3-3.7	0-3.7	1-9	0.4-1.2	0.5-2.7	0-6

ppb parts per 10^9

Table 3.3. Summary of Environmental Data on Black Angel Mine Tailings Discharge (Modified from Asmund 1992).

Amount of tailings	600,000 tons/year		
Operating period	1973-1990		
Average chemical composition mg/kg	Pb	2100	
	Zn	4200	
	Fe	164000	
	Cu	133	
	Ag	3.5	
	As	81	
	Hg	0.7	
Chemical treatment of tailings	$Ca(OH)_2$ $Al_2(SO_4)_3$ Magnaflok		
Flotation and pumping medium	Seawater		
Discharge depth	30 m		
Area of tailings deposit	0.6 km^2		
Metal release rate from tailings jet and submarine flow, tons/year		1975-81	1982-90
	Zn	55	28
	Pb	32	16
	Cd	0.57	0.28
Metal release rate from tailings deposit 1 year after close down, kg/day	Zn	18-33	
	Pb	_1-0.5	
	Cd	0.2-0.3	

_ Symbol in original table

Resampling of bottom sediments in August 1974 showed that contaminants were not being entirely contained in the sediment behind the sill in *A* fjord. The lead content in sediments just outside the sill in *Q* fjord were then 2.4 times background and the zinc was over 5 times background.

The natural (pre-mine operation) Black Angel geochemical anomaly was mirrored by elevations of constituent heavy metals in nearby seaweed and mussels. Biological samples taken in September 1974 (after nearly 1 year of mine operation), showed statistically significant increases in lead and zinc in blue mussels and seaweed at all nearby sampling locations. At this stage no additional heavy metal accumulations were found in either wolf-fish muscle or livers (Asmund *et al.*, 1975). Later studies by Bollingberg and Johansen (1979) on spotted wolf-fish caught in *Q* fjord showed statistically significant increases in the lead contents of both livers and kidneys but no increase of lead in the wolf-fish muscle. Since wolf-fish is essentially nonmigratory and feeds heavily on blue mussels they were sensitive to heavy metal contamination in living species close to the submarine tailing discharge. The above authors concluded that the increased lead levels in the wolf-fish were not a risk to public health.

As soon as metal contamination of biota from the submarine tailing discharge was detected, Cominco initiated research to both establish the cause(s) and seek remedies. Studies conducted by B.C. Research, (1977, 1978, 1979) established that while coarse fractions of the tailings sedimented rapidly and were largely confined to *A* fjord, fine fractions sedimented over a much wider area with minor amounts penetrating into *Q* fjord. They also eventually concluded that heavy metals initially dissolved in the tailing supernatant water at discharge (ie, from dissolution and reagent addition, of $ZnSO_4$ for example,) were almost insignificant in terms of total metals dissolved into the *A* fjord sea water (Table 3.2). Zinc discharged in dissolved form over one year comprised 0.7 tonnes while 26 tonnes of dissolved zinc accumulated in the *A* fjord following 6 months of tailing discharge in February 1974. Corresponding figures for lead were 0.28 tonnes and 14 tonnes respectively.

Eventually direct leaching tests by B.C. Research demonstrated conclusively that Black Angel mill tailing contained significant oxidized lead and zinc species that were rapidly soluble in sea water. Oxidation of residual heavy metal sulphides deposited in the inlet did not appear a significant contributor of the heavy metals release problem. Attempts were made to find chemical treatments that might inhibit dissolution of the soluble mineral or hydroxide precipitates. Even the damming of *A* fjord at the 21-24m sill between *A* and *Q* fjords was considered in order to confine the contamination to *A* fjord only. The latter was considered of highly questionable technical merit and would have been far too costly.

Testwork by the Cominco Technical Research Group at Trail, B.C. (Kuit, 1979) found that while available soluble metals (particularly Pb and Zn) were not actually in the solution phase in the tailing flow, dilution and reduction of pH to that of seawater (ca pH 8) combined to result in rapid release of soluble metals upon discharge to the *A* fjord. The available soluble metals, possibly anglesite ($PbSO_4$) or lead carbonate or lead hydroxide were also found to be largely concentrated in the fine solids in the tailing discharge. The Cominco Technical Research studies indicated that the Zinc Sulphate flotation reagent contributed a substantial proportion of the available soluble zinc to the fjord. The Cominco report recommended replacing this reagent, exploring use of other than $CaCl_2$-seawater brine for mine drilling, and evaluating $FeCl_3$ and $Al_2(SO_4)_3$ additions to inhibit dissolution of the tailings' heavy metals.

For a short period in 1978, Black Angel tailings were heavily treated with lime. This treatment was reported to reduce soluble lead levels from ~500ppb to 100-200ppb. Unfortunately the lime addition increased the release of soluble zinc complexes, and was discontinued.

3.7 Mine Closure and On-Going Monitoring

In April of 1986 falling lead and zinc prices prompted Cominco to close down the Black Angel mine. Based on a prior agreement, the Mineral Resources Administration (MRA) for Greenland was then entitled to make arrangement for continuation of the mine. This they did and in July 1986 Boliden AB acquired 100% of the share capital of Greenex A/S and the operation continued. In the new agreement (1986) with Boliden, US$11.6M (80M DKK @ 1993 exchange rate of 6.86DKK = US$1.00) was set aside for reclamation and closure costs. At the end of 1989 after index adjustment the amount of US$13.6M was available.

Recognized potential sources of contamination following the closure of Black Angel mine at Maarmorilik were:

1. Tailings in the *A* fjord
2. Dispersed metal-rich minerals on the minesite
3. Residues of ores and concentrates in the industrial area
4. Dusts where ores of concentrates were handled
5. Waste rock dumps, in particular the North Face Dump, which reached the fjord.

For source 1, after closure, and comprising undisturbed tailings on the fjord bottom, testwork indicated release of only insignificant amounts of lead. Source 2 was believed to be minimal. Careful cleaning was expected to eliminate sources 3 and 4. The waste rock dumps however were significant sources (Asmund, 1992). It was proposed to transfer the nearly 400,000 tonnes of waste rock in the North Face Dump into the *A* fjord where ca 8 million tonnes of mill tailings were already deposited. This waste dump was contributing significant lead, zinc and cadmium contaminants to the fjords as seen by the geographical distribution of lead in blue mussels and seaweed *Fucus* in 1989 (Figures 3.6 & 3.7). The highest levels of heavy metals in these biota were immediately below the North Face Waste Dump, which delivered contaminating metals to the sea surface water.

A summary of the use of marine organisms as indicators of heavy metal pollution at Black Angel mine over 16 years was presented by Johansen, *et al.* (1991). Seaweed, mussels, prawn, and liver and bone from both sculpins and wolf-fish were shown to be good indicators for lead contaminants in the seawater. Seaweed proved a good indicator for zinc contamination.

A useful review of the Black Angel Mine operation and state of reclamation one year after mine closure was published by Asmund (1992). This review concludes that during mine operation of 1973 to July 1, 1990, between 10 and 30 tonnes of lead, 30 and 55 tonnes of zinc and 300 and 600 kg of cadmium dissolved into the inlet each year. The environmental problems were primarily due to lead contamination. Figure 3.8 shows the tonnes of dissolved lead contributed

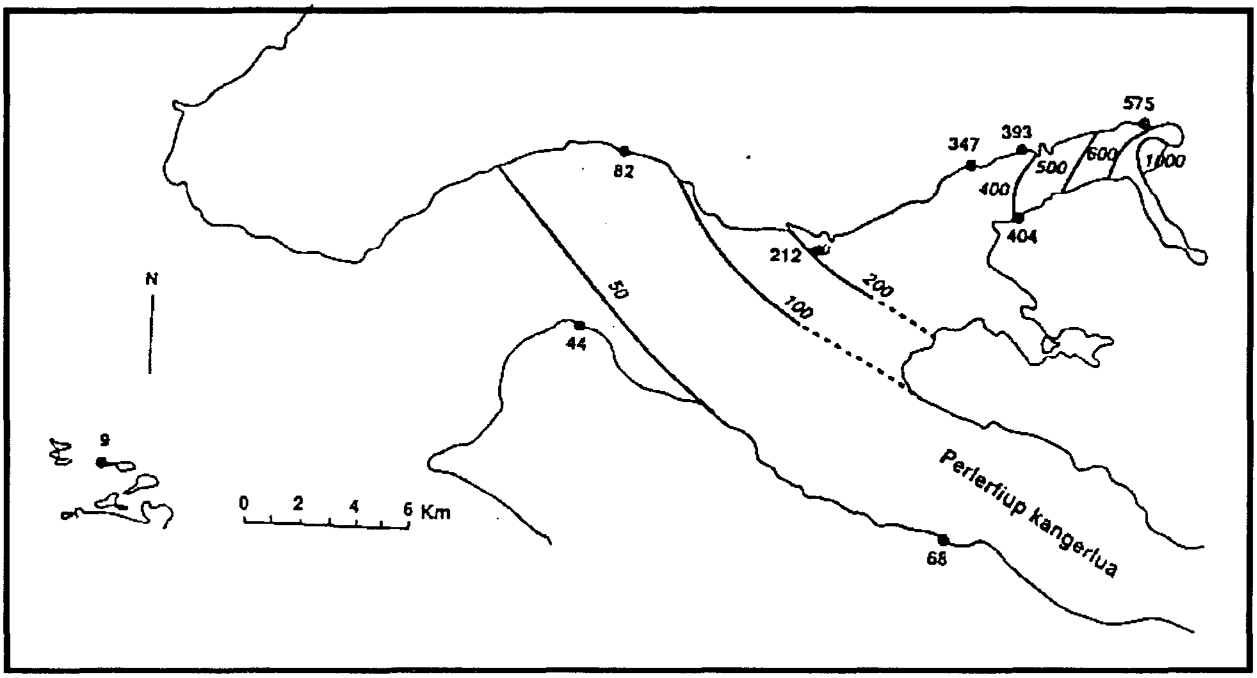

Figure 3.6 - Geographical Distribution of Lead in the Soft Part of the Blue Mussel "Mytilus edulis" to 1989 near the Black Angel Mine. mg/kg dry weight (Reprinted and modified from Asmund et al, 1990).

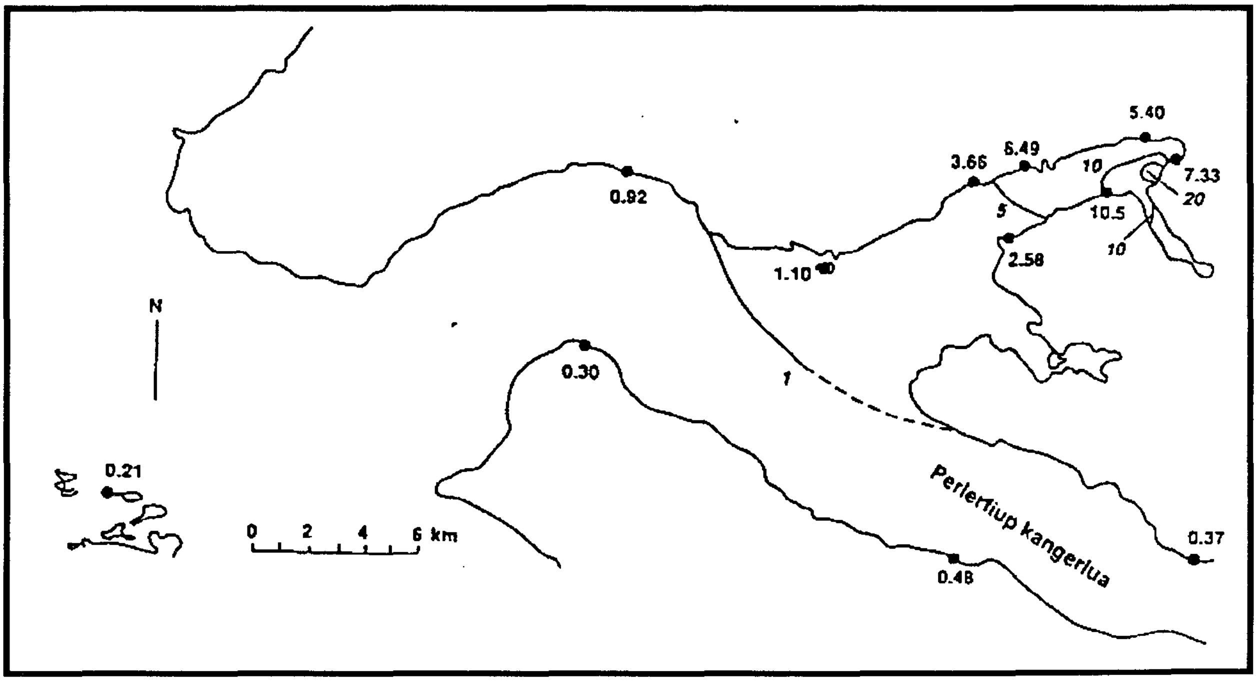

Figure 3.7 - Geographical distribution of Lead in New Growth Tips of the Seaweed "Fucus vesiculosus" for 1989 near the Black Angel Mine, mg/kg dry weight (Reprinted and modified from Asmund et al, 1990).

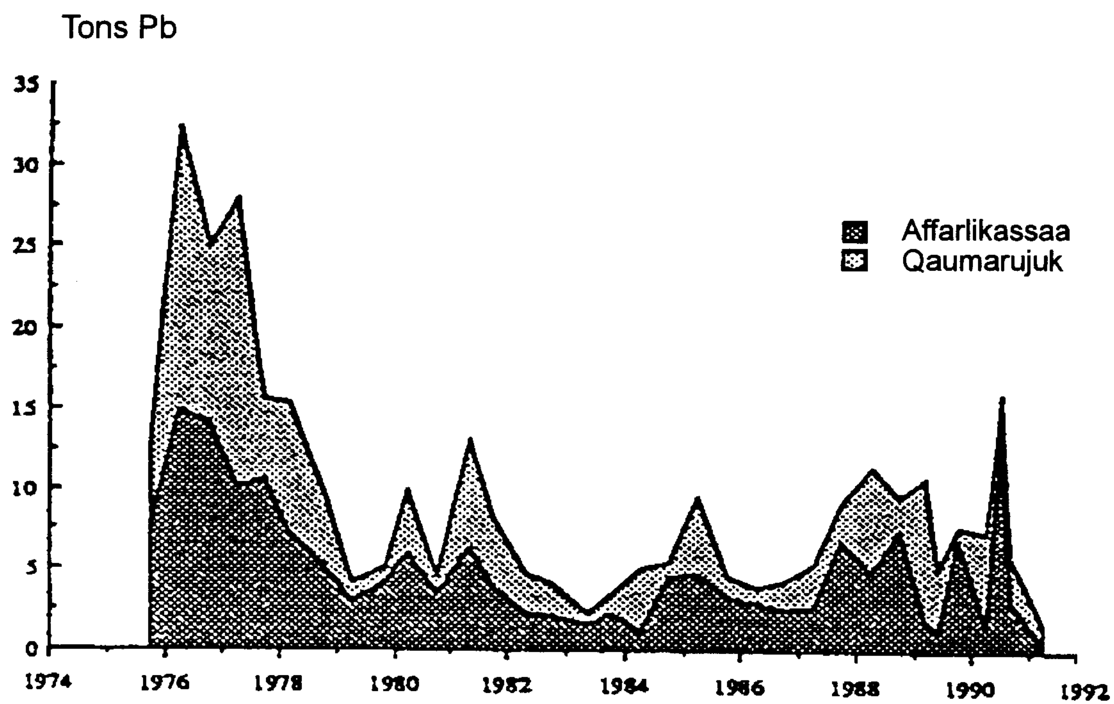

Figure 3.8 - Tonnes Dissolved Lead in "A" and "Q" Fjords near the Black Angel Mine (Reprinted and modified from Asmund, 1992).

to the *A* and *Q* fjords over the period from 1976 to 1991. Several changes made by the mine in 1979 significantly reduced the levels of lead release to the inlets (*i.e.*, from the order of 20 tonnes/year to ~5-10 tonnes/year see Figure 3.8). Some of the improvements included:

- improving recovery of Pb & Zn minerals to lower residuals of most heavy metals of concern in the tailings
- improving deaeration of the tailings prior to discharge to prevent secondary flotation of sulphides to the surface of of the fjord (see Asmund, 1992). Figure 3.9 shows type of deaerator installed
- minimizing billowing turbulence at the outfall itself by limiting outfall clearance above the fjord bottom to 2 meters. This was to minimize dispersion of fines into the upper part of the *A* fjord
- maintaining tailings pH above 10 at discharge to minimize dissolution of lead prior to settlement of the tailings solids
- Treating the tailings chemically with lime + aluminum sulphate + flocculant to reduce the dissolution rates by incorporating fines within floc aggregates which settle more rapidly to become a bottom sediment.

Monitoring of the *A* fjord waters and sediments, eight months after mine closure (in March of 1991), showed that settled tailings covered 0.6 km^2 of the 2.1 km^2 bottom area of *A* fjord and released ~30 kg of zinc per day and negligible lead per day. Table 3.3 gives a summary of the environmental data on tailings disposal at the Black Angel Mine.

3.8 Conclusions

Prior to marine discharge it was apparently assumed that the residual heavy metals would be present in the tailings only as insoluble sulphides. This was obviously not the case. In hindsight, it can be concluded that detailed mineralogical analyses could have shown that slightly soluble minerals were present. Direct sea water leaching tests on finely ground ore or simulated tailings would also have quickly indicated that significant solubility of Pb, Zn and Cd was to be expected at Black Angel.

More extended oceanographic studies through a full year would also have confirmed that the *A* fjord while stratified in the summer became well mixed during winter and spring. This resulted in transport of significant amounts of contaminants over the sill into *Q* fjord. Subsequent tailings bioassay studies by McGreer (1980) also showed bioaccumulation of activated metals by marine invertebrates.

In hindsight we can say that the initial STD design adopted was not effective in preventing trace metal contamination. A major environmental impact assessment program initiated when the contamination was detected led to operational controls being retrofitted to the milling process, and adjustments to the outfall. These substantially reduced the problems.

The Black Angel case history is a good example of the need for adequate mining and environmental information prior to detailed design of an STD system. In this case preliminary information on the local topography on land and underwater, and on the orebody, supported STD as the tailings management option in principle. Detailed further orebody and marine studies, that

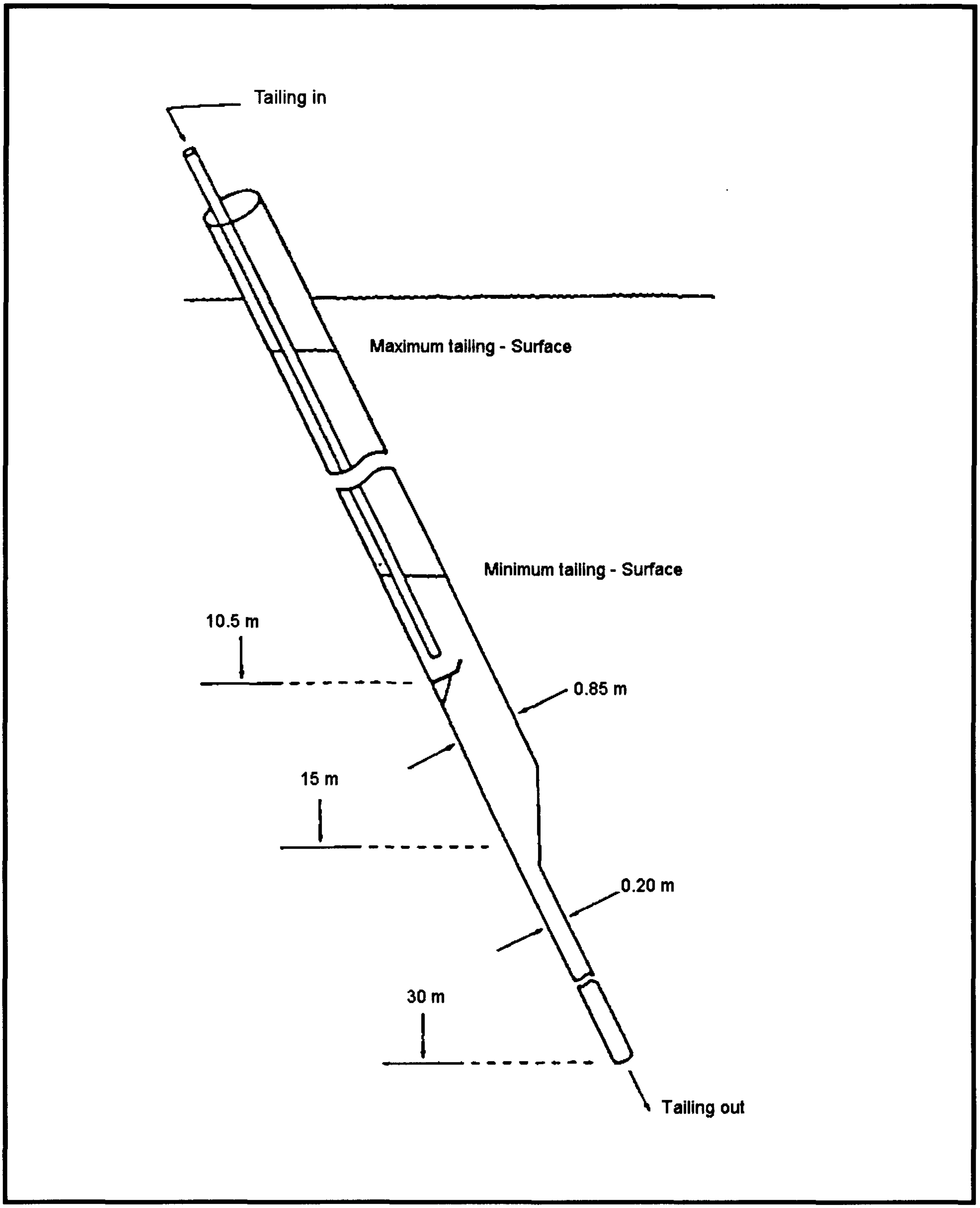

Figure 3.9 - The De-aeration System Retrofitted to the STD at the Black Angel Mine (Reprinted and modified form Asmund <u>et al</u>, 1988).

can now be seen as essential, would have produced information affecting the STD design and placement.

4.0 OTHER CASES OF STD: IN OPERATION AND UNDER DEVELOPMENT

4.1 Introduction

There are several examples of STD which are little-known for a variety of reasons. In some older cases, there has not been much information publicly available, or the information is scattered and not available in review format. Elsewhere new use of STD is only just being developed and documented.

Three case histories are described in this chapter, generally using the information that is publicly available in the scientific literature or government records. In some cases industry literature has been made available to us. The varying information sources from case to case mean that it is not possible to give equivalent information each time.

There are several mines in Norway which discharge their tailings to the sea either by STD or by beach or shallow water discharge. Although there is at least one summary document available (Anon, 1978), much of the information about the hardware and environmental impacts appear to be scattered through limited distribution reports. Crucial information to appraise the cases of STD, or to allow exploring whether STD is a viable alternative, is not readily available. Accordingly, we are not describing the Norwegian cases. Our reference (Anon, 1978) is a means of entering the literature.

4.2 Atlas Copper Mine (The Philippines)

4.2.1 Introduction

The Atlas Mine retrofitted STD to discharge its tailings to the sea in 1971. By 1981, 100,000 tonnes per day were being discharged. A description of the engineering was published soon after operation commenced (Salazar and Gonzales, 1973). Thus Atlas vies with Island Copper (Volume I) for being the first to adopt STD. Its system and engineering was somewhat different from Island Copper's, in part through the mines being located a few kilometers inland.

Atlas also differs from Island Copper in that the mine's follow-up environmental monitoring has been documented only by limited distribution reports based on Conference presentations (Dira and Canete, 1977; Salazar and Dira, 1980). In addition, Guevara (1981) provided responses to a questionnaire.

4.2.2 The Mine and Its STD System

The mine is located in the central part of Cebu Island, about 7 km from Tanon Strait. Reserves were estimated in 1973 at 700 million tons, with 30 years of mining anticipated for tailings discharge.

The major gangue minerals of the orebody are silica and silicates, with residual copper, pyrite, gold, silver, molybdenite and magnetite.

When STD was initiated in 1971, there were two concentrators serving two pits, Lutopan and Biga. There were four lines collecting the tailings from the concentrators. The pipelines were merged, passed through a 850 meters tunnel, and onto a 500 meters causeway and pipe pier at Ibo Point (Figure 4.2.1). Considerable attention was given to grind characteristics, flow hydraulics and engineering to ensure minimum sanding of the pipelines. Energy dissipation was achieved by pipeline orifices, rather than by drop-boxes. Sanding nevertheless occurred sufficiently that by 1973 drop-boxes and flumes were being installed, and more tunnels (with open launders) built to shorten the route to the sea. A third concentrator (Carmen) within 5 km of the others was added to the system in 1977, bringing the total of pipelines and launders to 47 km.

Discharge is at Ibo Point, selected from bathymetric surveys showing the presence of a trench with -15% slope near shore, leading to the Tanon Channel with depths of 350 meters (Figure 4.2.2) only 1.5 km from shore. A strong southeasterly shoreline current was expected to disperse suspended slimes. Depth at the discharge point was 30 m, with an average slope of -15%. Drop pipes with "90 degree bend nozzles" extend 10 meters below mean low sea water level.

Quarterly hydrographic surveys showed by 1973 that some nearshore tailings deposition had occurred (0.02% of total discharged), and "has stabilised at 12 meters below sea level in the area immediately below the discharge point" with slope approximately -20%. This was again reported by Salazar and Dira (1977) and Dira and Canete (1980). It is implicit in the three industry reports that the density current maintained the flow towards the targeted incised channel. Salazar and Gonzales (1973) reported that there was some deposition back of the discharge point, but that there was no evidence of tailings surfacing along the beaches. Also surface turbidity was confined to within 5 meters of the discharge point.

Salazar and Gonzales (1973) also report, but without supporting documentation, "The disposal of Atlas plant tailings at Ibo has no adverse effects on marine life in the area. In fact, the discharge point at Ibo has become a favorite fishing ground of fishermen in small native boats (bancas)."

However, Salazar and Dira (1977) and Dira and Canete (1980) refer to government marine environmental surveys from 1972 to 1973. The reports stated essentially that there was no significant effect on plankton. Benthos was absent in an area extending 3.5 km from the shoreline and extending 6 km on both sides of the discharge point parallel to the shoreline. Tested physical and chemical conditions were within ambient levels. Acute bioassays with Tilapia gave 100% survival at tailings concentrations from 10% to 56%. Interviews with local fishermen established that catches had not been affected.

Nevertheless by 1981, Alino (1984) found, during university thesis studies (Alino, 1983), evidence for some elevated sedimentation, metal contamination and coral cover around the outfall. Elevated copper levels in sediments in traps, with highest values closest to Ibo Point indicated that some tailings were surfacing. Coral cover was reduced close to Ibo Point. The

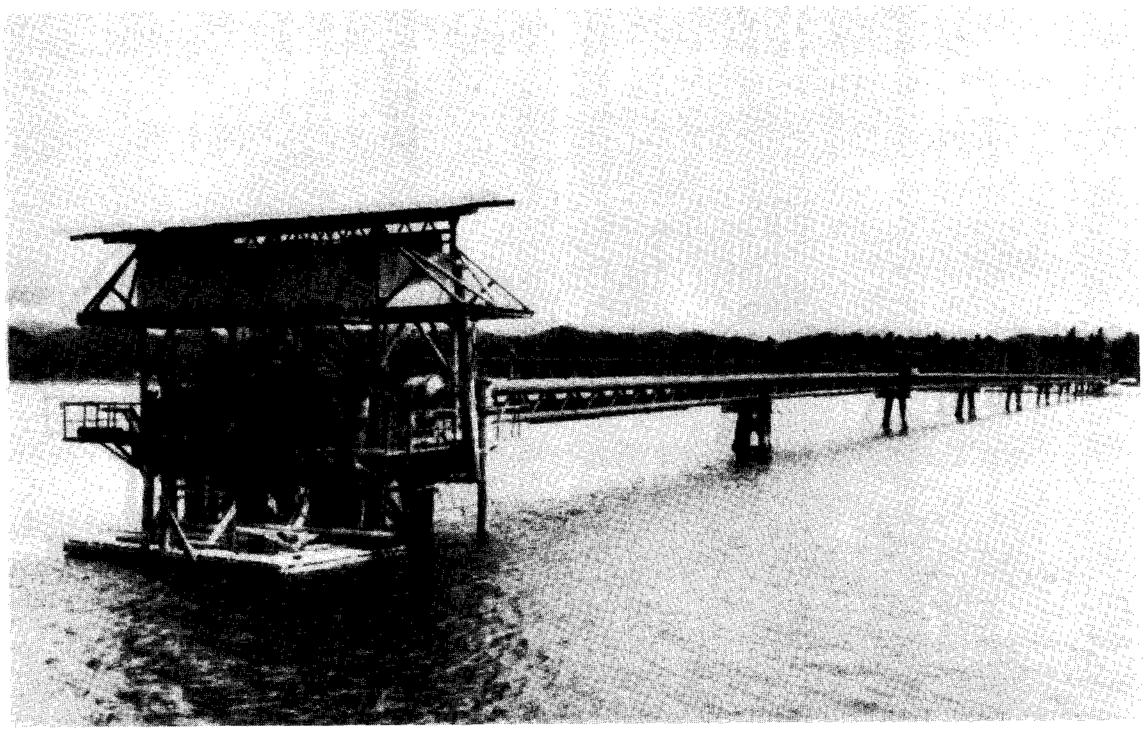

Figure 4.2.1 - The Tailings Causeway and Discharge Point for the Atlas Mine (Rephotographed from Salazar and Gonzales, 1973).

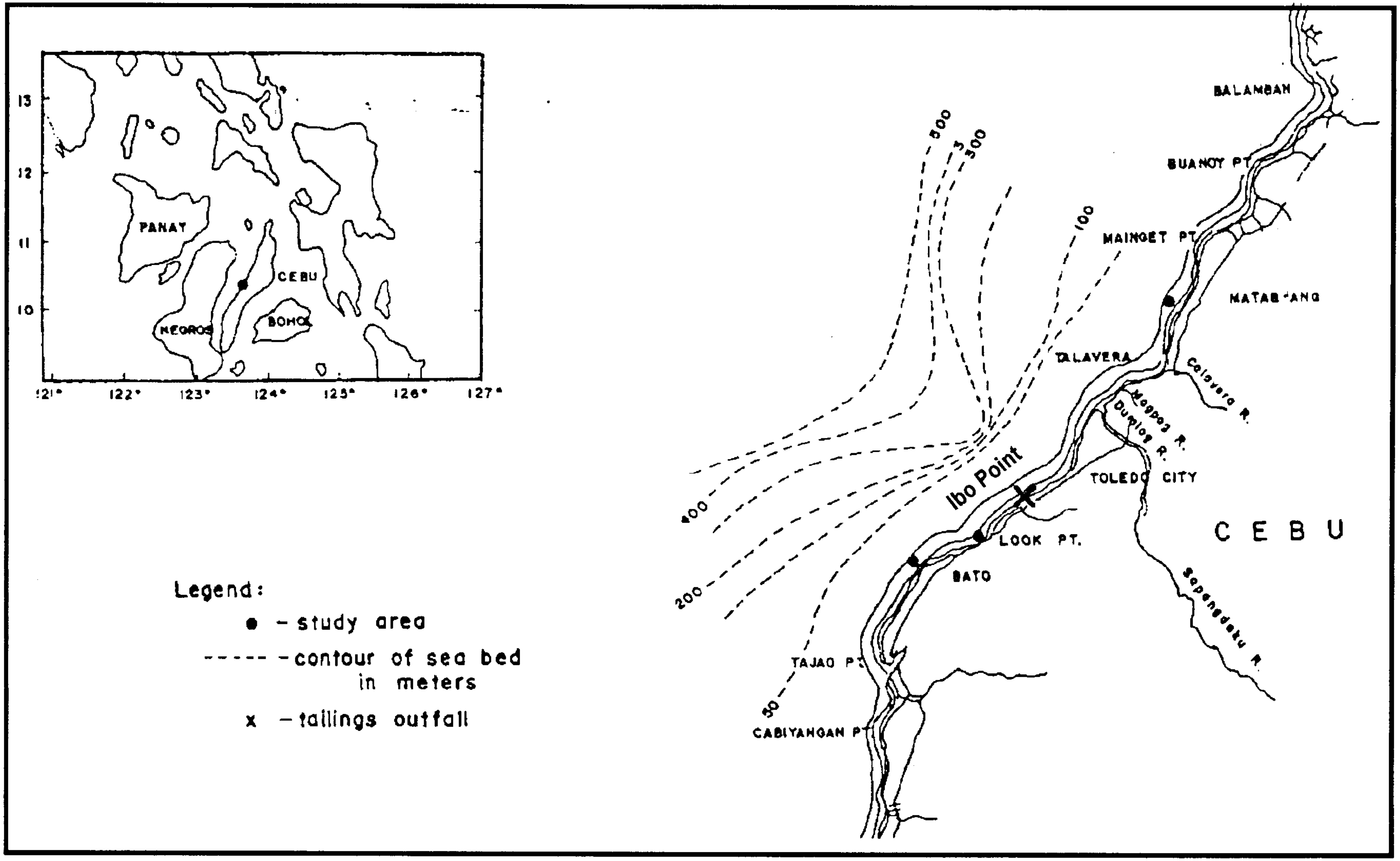

Figure 4.2.2 - Bathymetry Offshore from the Atlas Outfall Location at Ibo Point (Reprinted and modified from Alino, 1984).

scarcity of local references in Alino (1984) indicates that there was little environmental data available during the time of his investigations, or if there were such data in government or industry files it was not publicly available.

In summary, the STD system installed appears to have achieved its design function of directing the major part of the tailings stream to depth. The outfall design adopted allows some minor secondary plumes of fines to upwell and can be seen to drift behind the drop-box towards shore, and then disperse in the surface currents. The retrofit in 1971 thus prevented further losses of agricultural land in the original valley receiving the tailings and the downstream coastal plain, and further siltation around the mine's loading dock.

The major environmental impact reported is absence of benthos over an area 3.5 x 12 km. Results from Island Copper Mine and Kitsault (Volume I), and the Toquepala and Cuajone Mines in Peru (Section 4.5) contrast with this and establish that substantial numbers of benthos can occur on stabilised tailings. Details of the sampling gear used in the single survey are not available to us, but if a fisheries trawl was used, it would not collect the type of benthos reported from Canada and Peru.

4.3 Cayeli Bakir Copper-Zinc Development (Turkey)

4.3.1 Introduction

This mine is developing a unique system of STD, in that the discharge is to a deep inland sea (The Black Sea) with anoxic water below about 175 m. Thus it can provide the first information on the marine geochemistry from STD into deep high sulphide seawater.

4.3.2 The Mine and Its Proposed STD System

Cayeli Bakir is a copper-zinc mine being developed 7 km from the Black Sea coast in the Buyuk Dere Valley (Figure 4.3.1).

According to Rescan:

> The Cayeli Bakir mineral deposit is of igneous submarine origin dating from the upper Cretaceous era. The host rock, or igneous intrusion consists mainly of very fine grained basalt and tuff. The mineral deposit is a massive sulphide consisting of greater than 72% Pyrite (FeS2), 14% Chalcopyrite (CuFeS2), 11% Sphalerite (ZnS), 1% Galena (PbS) and 2% Gangue.
>
> Mineral processing will require grinding the ore to a median grain size of 20um, thus resulting in a very fine grind. The tailings solids will consist, primarily of Pyrite with a specific gravity of approximately 4.8. (1992a)

The mine is permitted to discharge annually "...427,000 m^3 of solids slurry and 4,000,000 m^3 of treated liquid and all other kinds of wastes...." This shall be ".. discharged into the anoxic deep waters of the Black Sea..." (Rescan, 1992b). Initially discharge is expected to be at the rate of 1296 tonnes per day. Predicted chemical characteristics of the tailings stream in the context of Turkish Receiving Water Quality Criteria are given in Table 4.3.1.

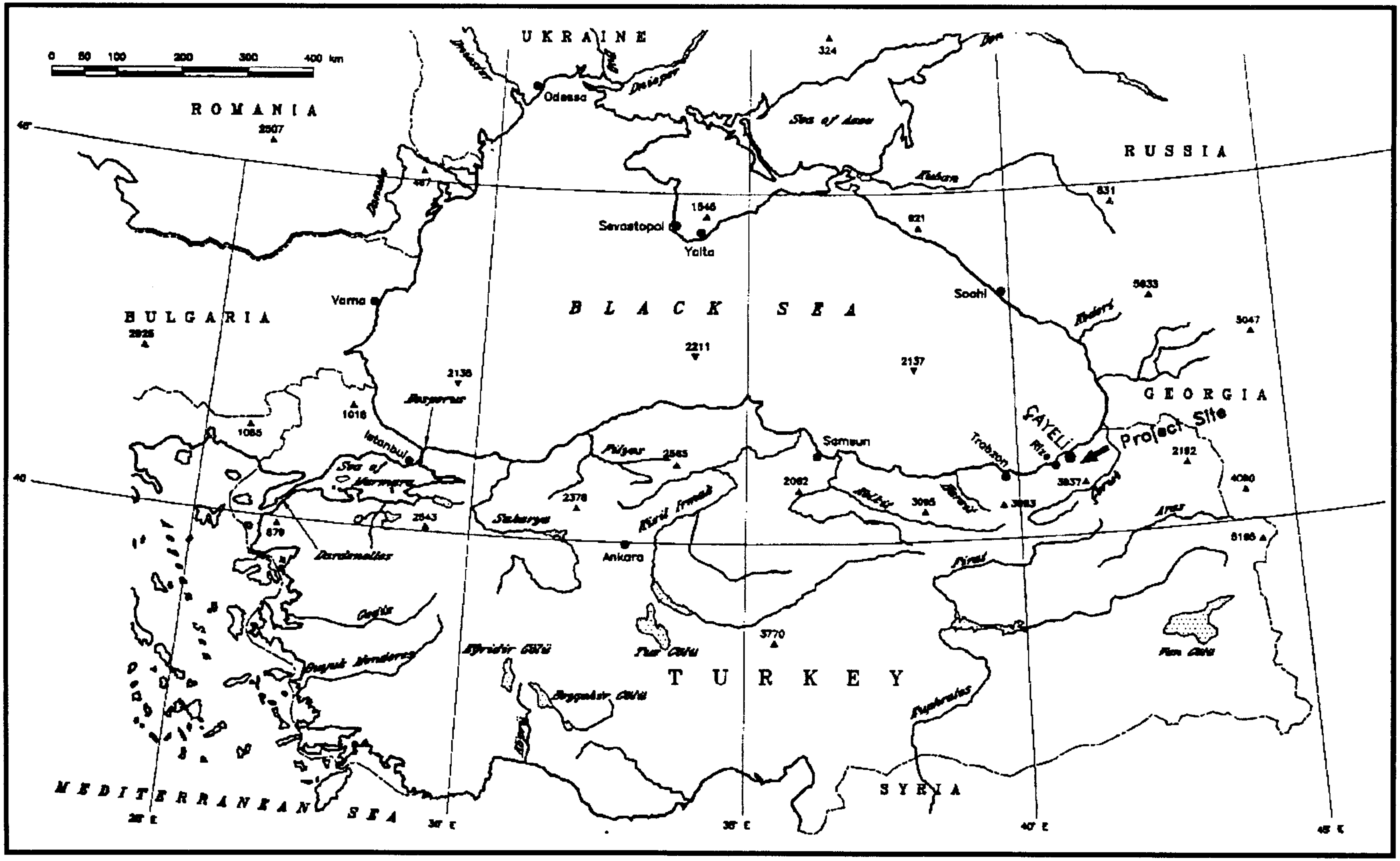

Figure 4.3.1 - Map of Turkey and the Black Sea Showing Location of the Cayeli Bakir Mine (Reprinted and modified from Rescan, 1992b).

Table 4.3.1. Turkish Marine Receiving Water Quality Criteria and Expected Chemical Characteristics of the Tailings Discharge at the Cayeli Bakir Mine (From Rescan 1992a).

Element[1]	Concentration in Tailings Water	Mining Industry Allowable Discharges	Receiving Water Quality Criteria for General Sea Water[2]	Deep Sea Discharge Limits
Cu	0.02-0.05	5	0.01	
Pb	0.01-0.05	0.5	0.1	
Zn	0.1-2	3	0.1	
Fe	0.05-0.1	3		
Cr	<0.01	2	0.1	
Mn	0.01-0.3			
Hg	<0.001	0.06	0.004	
As	<0.05	3	0.1	
Ni	<0.05		0.1	
CN	<0.03	0.1		
Total P				10
Total H				40
Oil & Grease				10
BOD				250
COD	110-250	80		400
Coliforms				note [3]
pH	11		6-9	6-9

Note [1] Units are milligrams per litre (mg/L) unless otherwise noted.
Note [2] Receiving water quality criteria apply at the outer edge of the mixing zone usually taken as 100 m from the outfall terminus.
Note[3] Coliform limits apply only in bathing areas and therefore are not applicable in this case.

The tailings disposal system utilizes the anoxic conditions of the Black Sea below about 200 meters depth, with H_2S concentrations greater than 3 mg/l. The depths are therefore devoid of life other than sulphur metabolising bacteria, and the H_2S levels serve to precipitate dissolved heavy metals. These depths are consistent indicating no upwelling. Below 100 meters depth, currents approximate <2cm/second.

A steep slope approximating 30% is located about 2 km from the shore off the discharge point (Figure 4.3.2) and a lesser slope then extends to depths exceeding 1000 meters about 5 km from shore.

The regulatory agency did not accept an initially proposed 150 meters discharge depth, but increased it to 350 m. This has added substantially to the cost and technical difficulties in installing and maintaining the system. Wave height and swell analyses have been made to establish outfall design criteria.

A submarine canyon approaching within meters of the shore (Figure 4.3.2) was rejected as a natural flume to receive the density current. Inspection by ROV (Remotely Operated Vehicle) showed that sections were rocky and precipitous, and deposited sediments were unstable. The 350 meters discharge depth requirement prohibited discharging to the canyon laterally further offshore, for instance at 150 meters depth just below the anoxic layer.

Rescan (1992c) specifically identifies potential pipeline failure modes, avoidance actions and repair procedures (e.g. submarine slope instability--especially in the nearby submarine canyon, vessel operations such as fishing, dredging and anchoring, storm damage and blockage from extraneous material).

Tailings density current behaviour has been modeled (Figure 4.3.3), and a performance evaluation of the outfall is intended (as at Misima - Section 2) after start-up.

A seawater intake pipe extends 500 meters offshore to 12 meters depth. A deaeration chamber will be built at 3 meters water depth.

Fisheries in the eastern Black Sea are important. Rescan (1992a) states "The eastern Black Sea contributes approximately 57% of the total Turkish sea fish harvest, with the major harvested fish species being European Anchovy, Horse Mackerel and whiting. The area also contributes 23% of the total Turkish shellfish harvest."

The Black sea has been subjected to many years of oceanographic and marine biological investigation, e.g. Black Sea submarine topography (Figure 4.3.4). This was available to the mine's environmental consultants and reviewed by them (Rescan, 1992b). The existing data determined the scope of additional environmental surveys, such as the need to confirm deep water chemistry (Figure 4.3.5), currents and circulation, water quality and oceanography, and wave severity. A continuing monitoring program during operations has not yet been developed.

The project has been reviewed by the Environment Unit of the World Bank/International Finance Corporation (WB/IFC, ND).

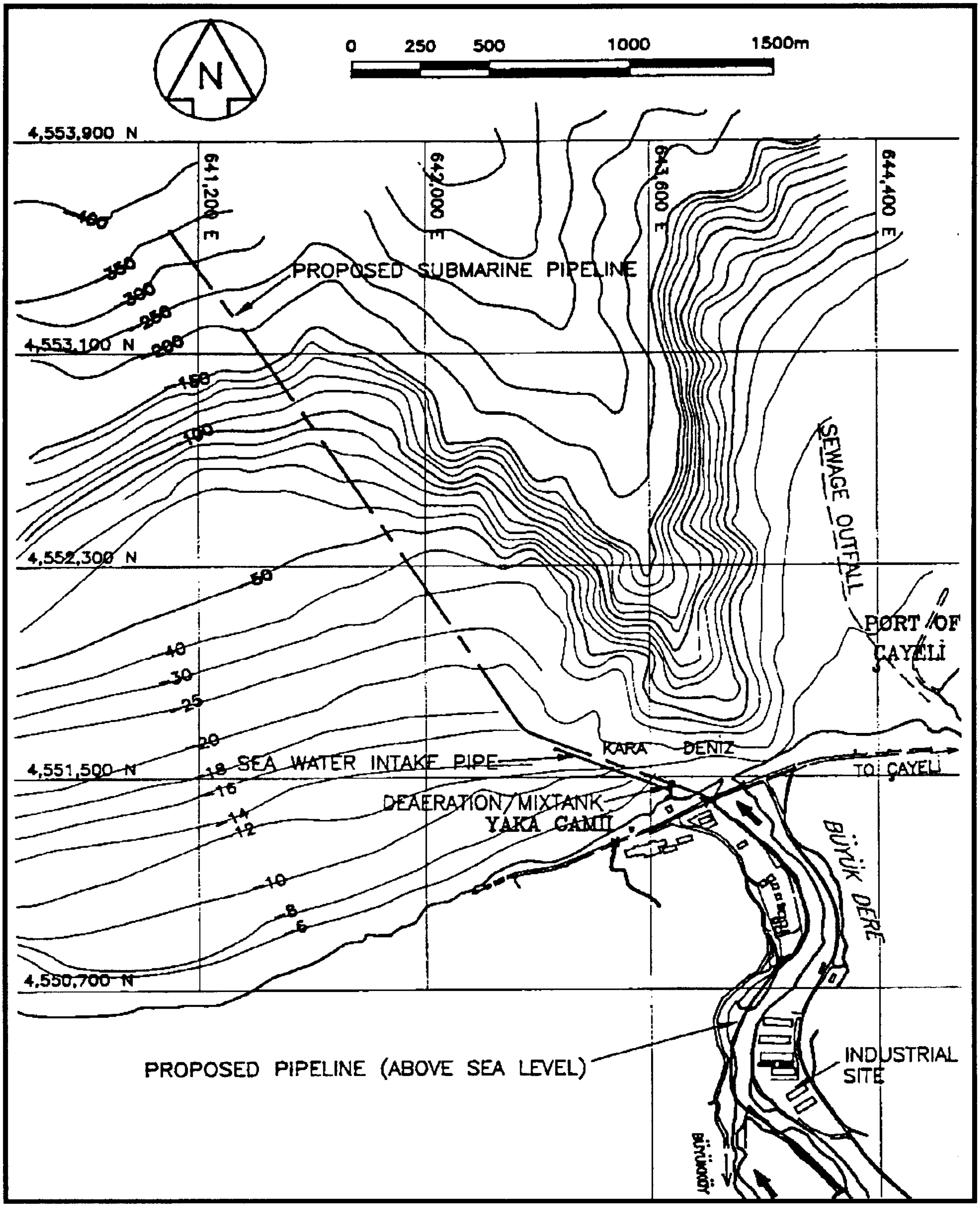

Figure 4.3.2 - Bathymetry at the Permitted Point of Discharge for the Cayeli Bakir Mine (Reprinted and modified from Rescan, 1992a).

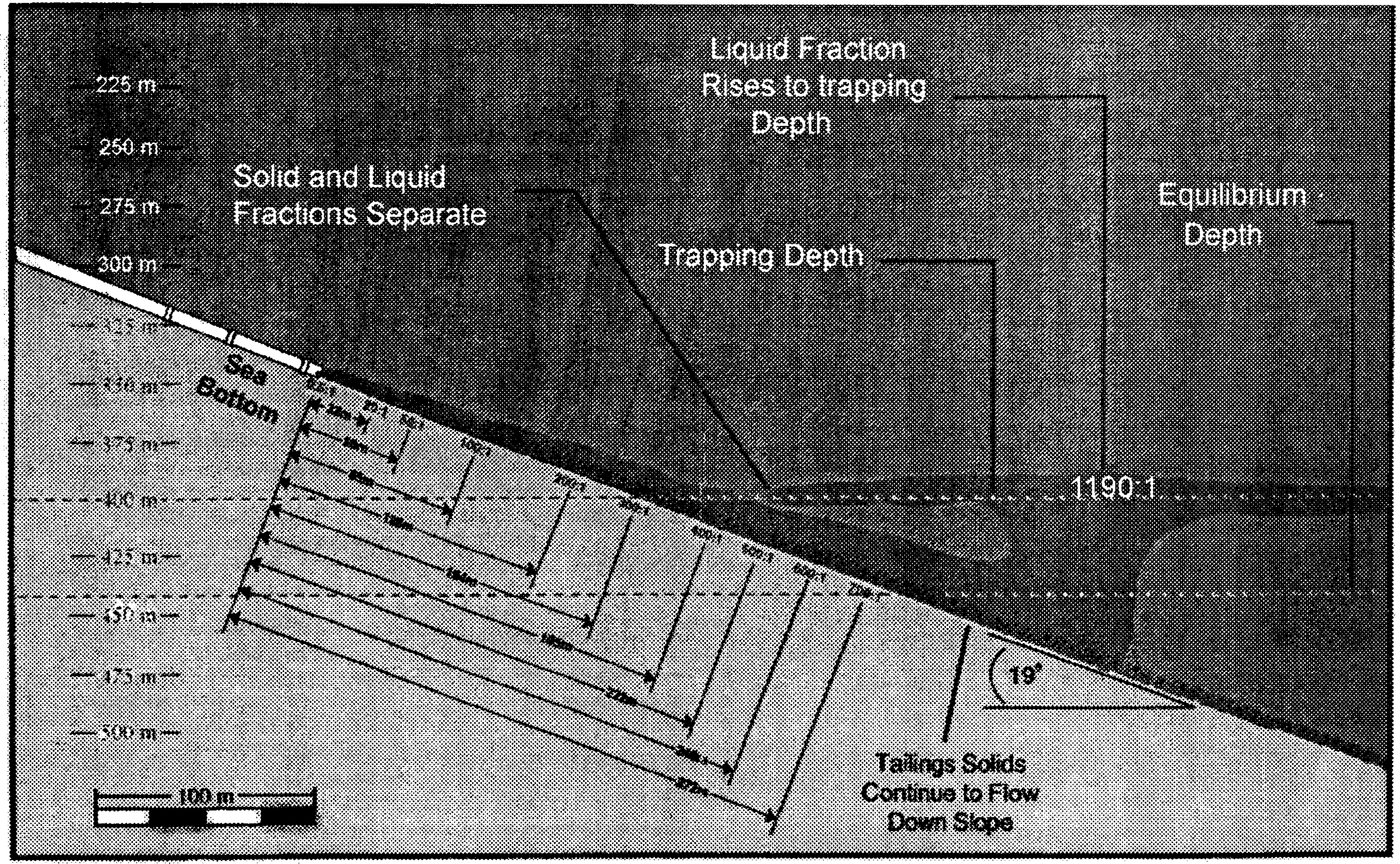

Figure 4.3.3 - Tailings Plume Dispersal Model for the Cayeli Bakir Mine (Reprinted and modified from Rescan, 1992b).

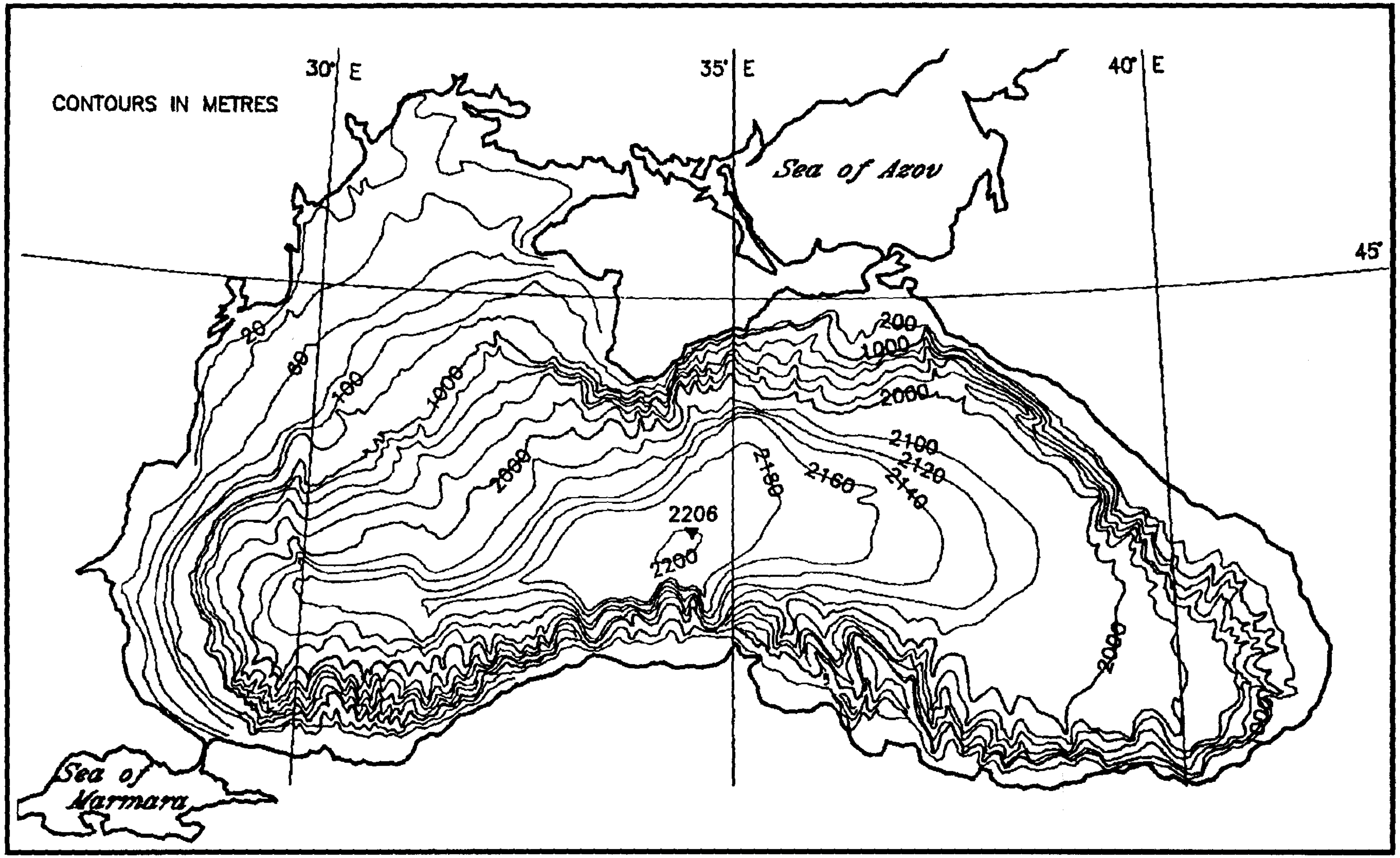

Figure 4.3.4 - Bathymetry of the Black Sea (Reprinted and modified from Rescan, 1992b).

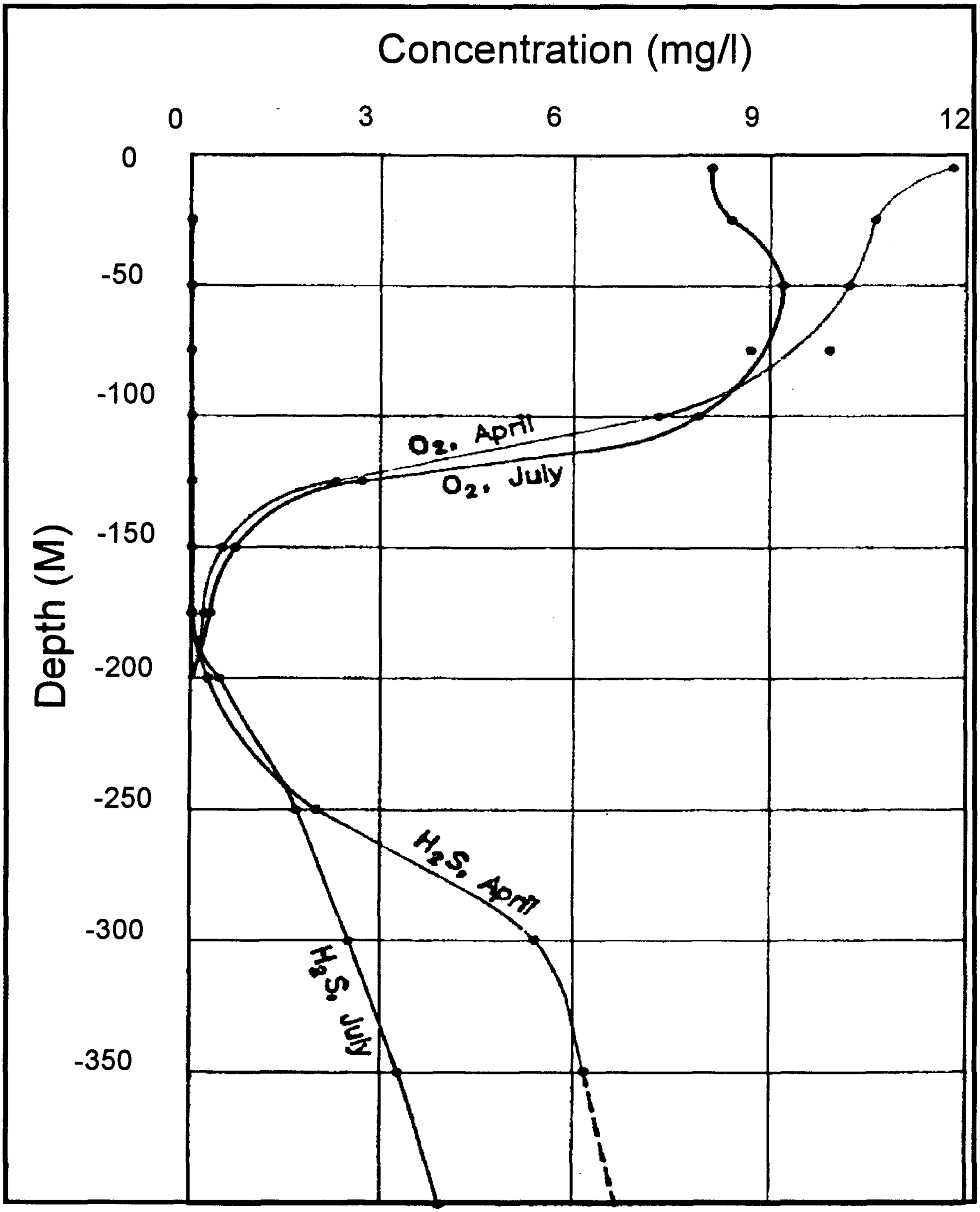

Figure 4.3.5 - Profiles of Dissolved Oxygen and Hydrogen Sulphide near the Discharge Point for the Cayeli Bakir Mine in April and July 1992 (Reprinted and modified from Rescan, 1992b).

The outfall now permitted will be the world's deepest and longest at 350 meters depth and 3.5 km respectively.

4.4 Toquepala and Cuajone Mines (Peru)

4.4.1 Introduction

The importance of these mines located in southern Peru (Figure 4.4.1) is that STD is being retrofitted to an existing system discharging tailings from two adjacent large open pit mines to a river.

The lower River Locumbo and some of its headwaters effectively have been turned into open tailings flumes, eliminating fish and other biological resources. A 10 km long tailing beach has formed prograding 1.3 km seaward. The proposed STD is designed to stop this prograding, and to constrain lesser evnironmental impact to below a discharge of 20 meters.

The application of STD is unique in that discharge is relatively shallow, and to a high-energy, wave-swept coastline.

4.4.2 The Mine and Its Proposed STD System

The mines are located approximately 100 km inland (Figure 4.4.1), and are large open pit operations generating approximately 100,000 tonnes per day of tailings from the two mills. Southern Peru Copper Corporation (SPCC) is the operator.

Ore composition is primarily sericite at 35%, quartz 25%, chlorite 12%, biotite 8%, kaolinite+monmorrilonite 8%, sulfides 7% and tourmaline 3%.

The mill process is shown in Figure 4.4.2. Tailings are transported by a mix of canals and dry creek beds to the channel of the Locumba river. The input point is just below where the river has been diverted as a water source for the town of Ilo. From there the tailings flow down the dry river bed to a beach, the Playa Inglesa, within Ite Bay (Bahia de Ite).

Longshore currents and strong surf have worked the depositing tailings into a 10 km beach 1.2 km wide at low tide (1.3 m). There is an obvious surface plume approximately 1 km long.

Near highwater mark, within 2 km of the River Locumbo channel, segregation of light and heavy minerals has produced in places a 1.5 meters thick banded deposit of pyritic sands. Percolation of water through these sands has resulted in oxidation of the pyrite. The resulting acid generation and concomitant heavy metal solubilization will be a significant source of contamination to seawater and marine organisms.

In contrast, more distant from the tailings outflow freshwater seeps from irrigation of adjacent farmland terraces have generated a series of backshore coastal wetlands. These serve as wildlife habitat, and are used for pasture by tended goat herds (SPCC, 1992; Figure 4.4.3).

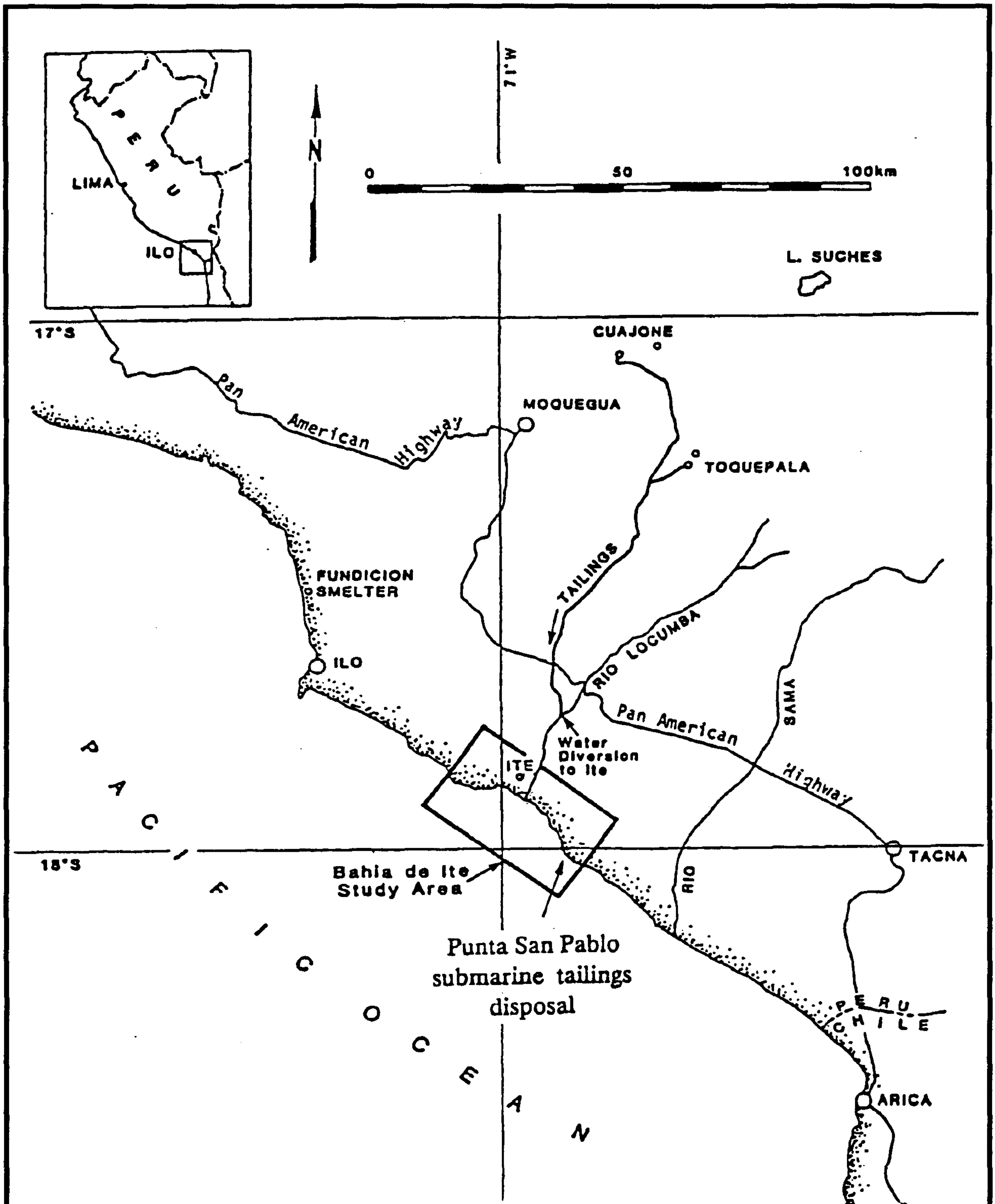

Figure 4.4.1 - Map of Southern Peru Showing Location of the Toquepala and Cuajone Mines and the Onland Tailings Transport System (Reprinted and modified from Rescan, 1992).

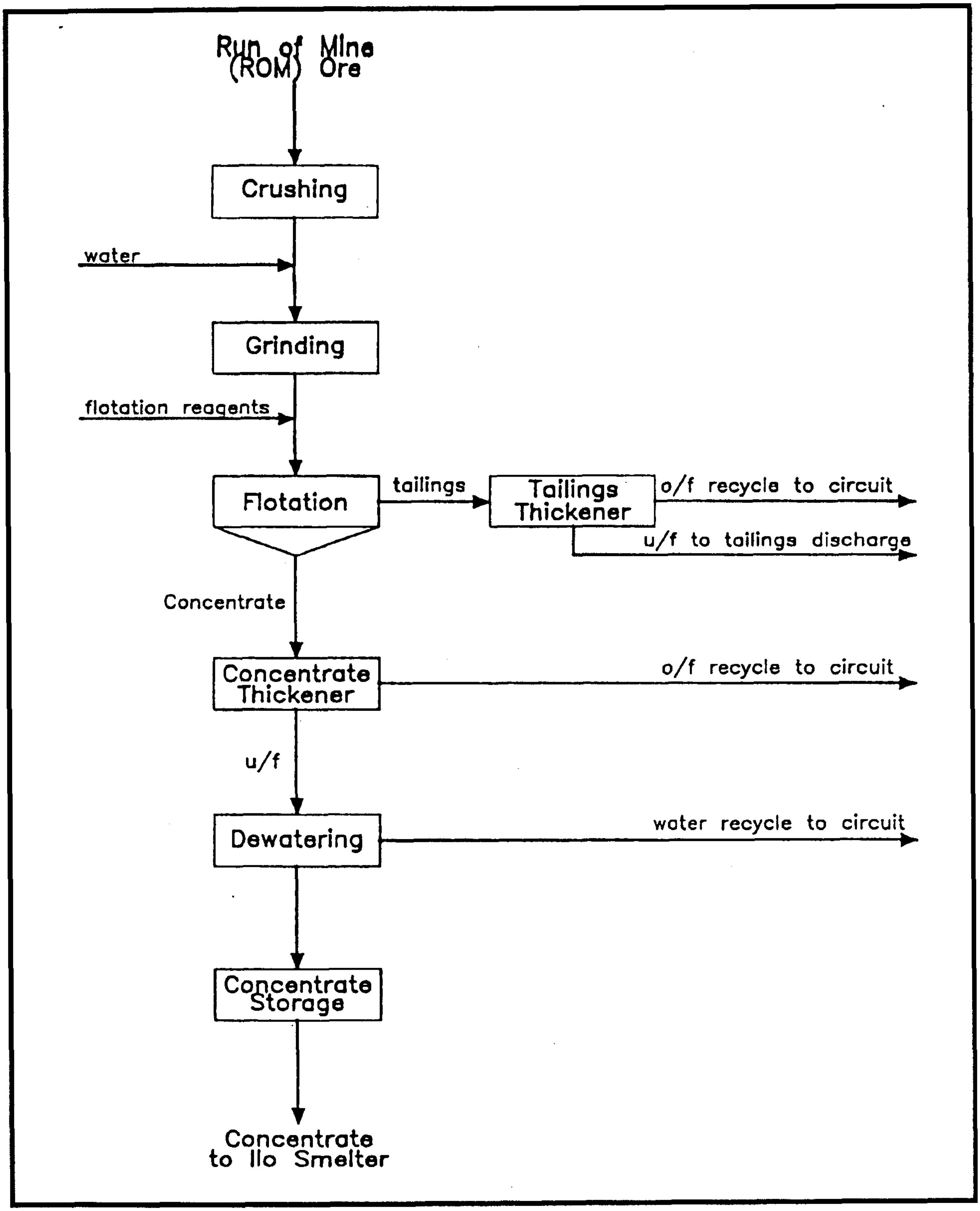

Figure 4.4.2 - Simplified Process Diagram for the Toquepala and Cuajone Mines (Reprinted and modified from Rescan, 1992).

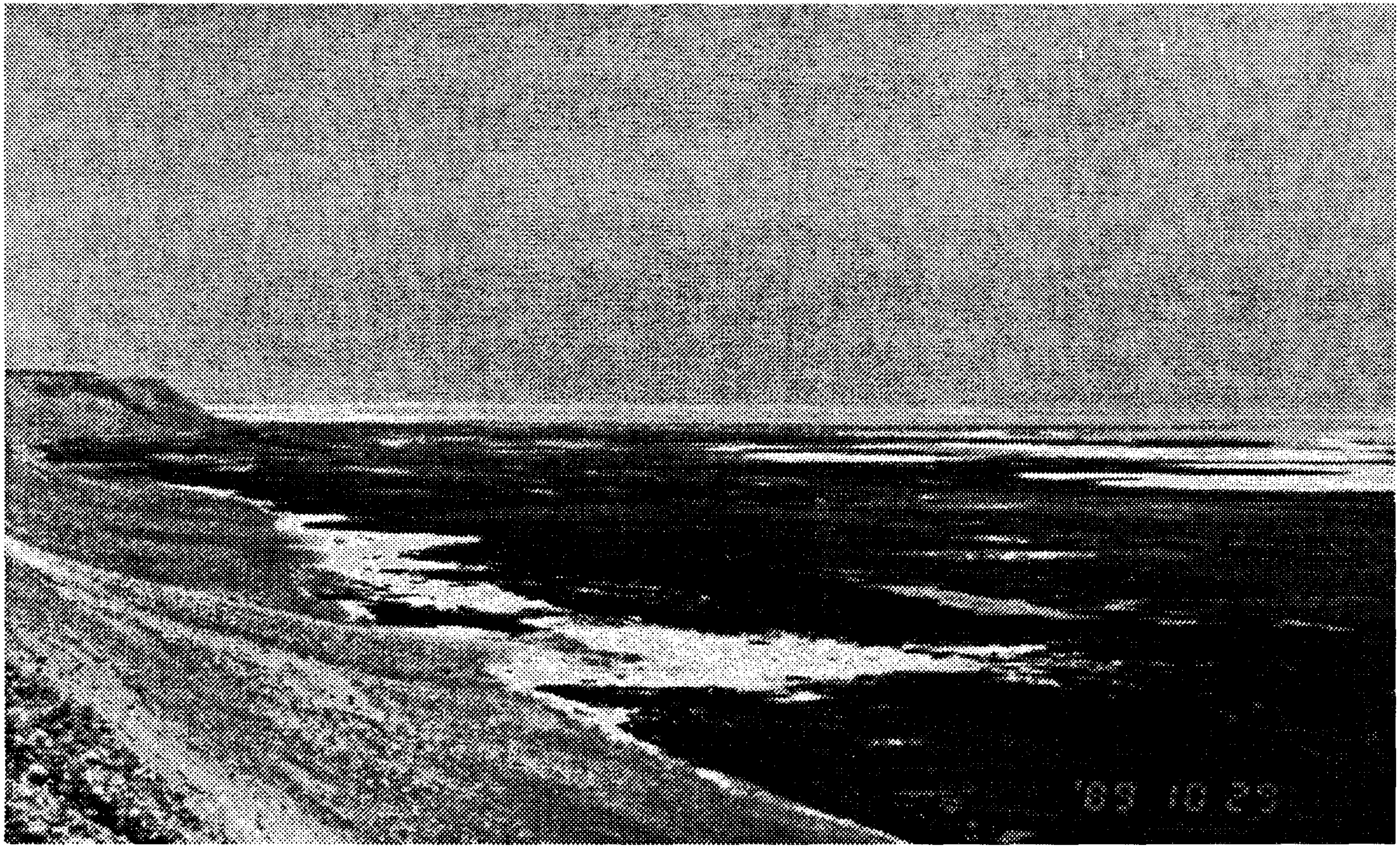

Figure 4.4.3 - The Development of Freshwater Wetlands on the Backshore of the Beach formed by tailings from the Toquepala and Cuajone Mines (Reprinted from a color photograph in Rescan, 1992).

There has been very substantial physical degradation of the intertidal environment, with productive rocky shores replaced by a barren tailings beach. The impoverishment undoubtedly continues offshore, but by 36 meters depth a benthic fauna occurs similar to that elsewhere (Rescan, 1992).

Rescan (1992) identifies a needed comprehensive environmental impact assessment and subsequent monitoring program. This encompasses physical oceanography, sedimentology, water quality, the fishery resources, and marine ecosystem structure and dynamics.

There has been some community action responding to SPCC's proposal for STD. This has been incorporated within a generalised reaction against SPCC developments and management, culminating in a complaint by Associacion Civil "Labor" to the 2nd International Water Tribunal (IWT, 1992, Diaz *et al.*, 1991). The complaint refers to mine, water intake and smelter environmental management as well as to tailings disposal.

The 2nd International Water Tribunal, a non-governmental organization, was held for open discussions of water management in 3rd world countries, and to make recommendations (IWT, 1991). The Tribunal basically accepted the complaints of Labor, and recommended that SPCC "invest sufficient amounts for the improvement of its environmental performance, including installation of secondary treatment, introducing more modern copper processing technology, minimizing environmental impact and remediating existing impacts." (IWT, 1992).

At the IWT, one of the authors (DE - Member of a Committee of Experts appointed to assist the IWT jury) discussed STD with the Labor delegates there. It became apparent that there was a consistent hostility to STD in principle. It appears that this is based on the conventional wisdom that (1) tailings in sea water must leach their toxins, and (2) coastal upwelling of deep offshore water must continue into shore and sweep back to shore the tailings deposited at depth.

In the context of toxin leaching, low oxygen conditions below 20-30 meters depth (See below) add to the ambient reducing conditions, and the risk of such leaching is negligible (See the MEND reports described in Section 1.2).

In the context of surface upwelling of tailings, the consistent oxygen stratification shows that the well-known deepwater upwelling (low oxygen water) from the Peru Coastal Undercurrent rarely if ever comes inshore to impact on the beaches. The major threat for resuspension and surfacing of tailings comes from extreme storm-generated wave action and temporary destratification of the water column.

The STD concept adopted by SPCC is to pipe tailings from an intake point on the River Locumbo some 6 km inland, and transport them by gravity flow in a 25 km pipeline to Pta San Pablo (Figure 4.4.4). At the Point, tailings will pass through a de-aeration chamber and be mixed with seawater taken from 5 meters depth. The tailings will then be discharged at a depth between 12 and 20 meters (still to be finalised) about 170 meters offshore. They will then flow by density currents to deposit from about 20 meters depth on the sloping shelf.

A temporary offshore pipe by the River Locumbo will bring some immediate amelioration of the existing beach impact.

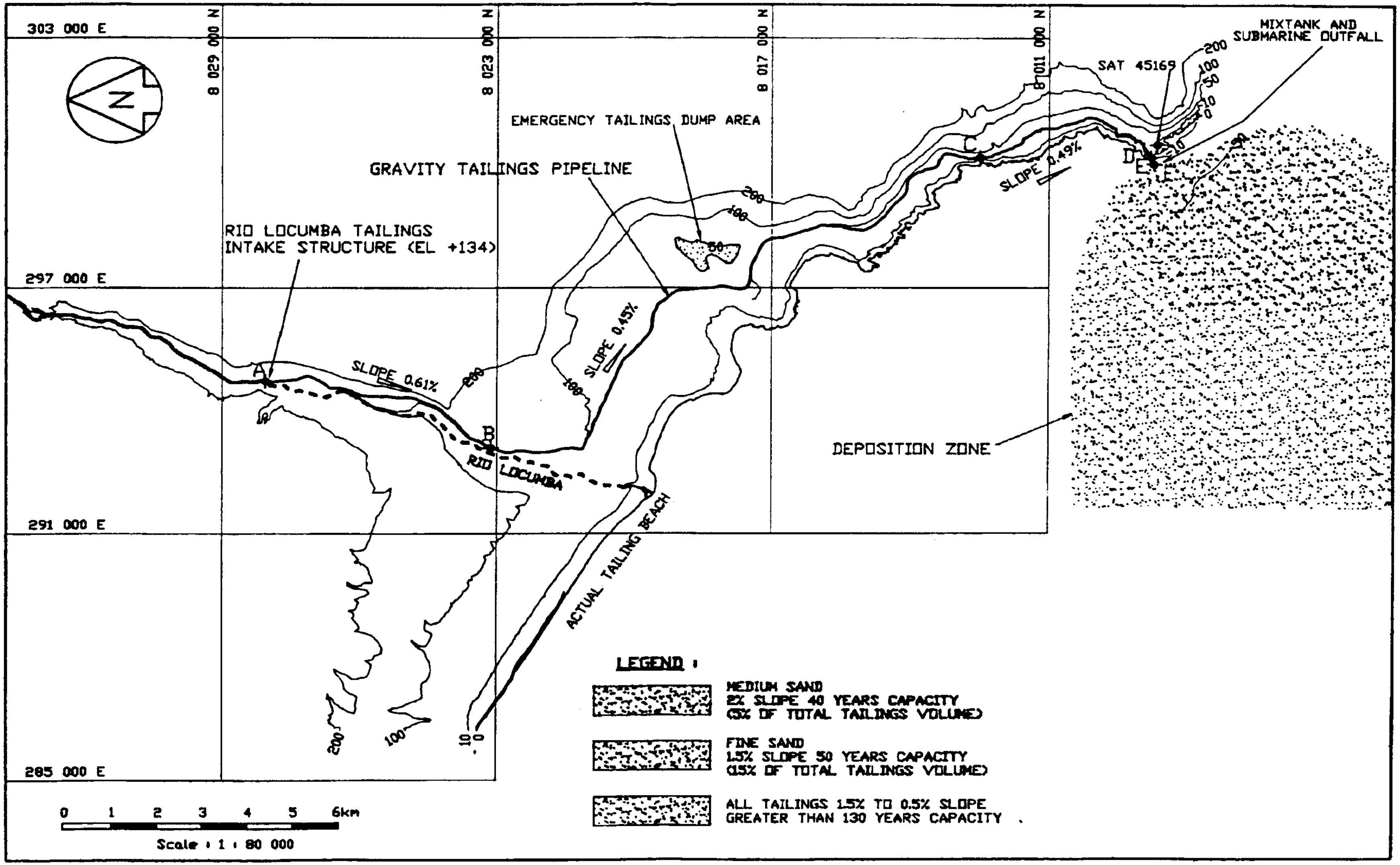

Figure 4.4.4 - Tailings Pipeline Route Developed for the Proposed STD for the Toquepala and Cuajone Mines (Reprinted and modified from Rescan, 1992).

The STD system proposed is relatively shallow compared to others built, under construction or being considered. Rescan (1992) reports on the site-specific physical oceanographic surveys and plume dispersal modeling studies undertaken for prediction of the deposition pattern in this currently novel situation. Below 20 meters depth, predominant currents average 12 cm/sec to the southeast, in contrast to stronger surface currents setting to the northwest. There is no evidence for seasonal upwelling returning suspended fines to the surface, nor resuspending fines once deposited.

In addition, at about 20 meters depth there is a marked oxycline. Below that depth, low oxygen levels are generally less than 2.0 mg/L. This is derived from upwelling deep water. This will facilitate the development of reducing conditions within the tailings by SRB (Sulphate Reducing Bacteria - See Ch. 1.2)

An extensive EIA is in progress to determine physical, chemical and biological oceanography. Initial objectives are (1) to establish the potential for tailings suspension, resuspension and upwelling, (2) the chemical potential for contaminant bioactivation, and (3) the extent and productivity of the biological resources, (*i.e.* the fishery resources and their benthic feedstock ecosystem).

In summary, the STD system proposed by SPCC is novel in that it will discharge tailings to a platform extending broadly offshore from 20 meters depth. This is shallow relative to existing use of STD. The system is considered practical and with low environmental risks at this site for two reasons. Unusually low oxygen levels derived from deep water upwelling will facilitate formation of a reducing ambient environment within the deposits, hence eliminate trace toxin leaching. Upwelling of discharged tailings before or after deposition is of low risk, and dependent on extreme temporary storm events, not from deep-water upwelling from the Peruvian Coastal Undercurrent.

5.0 THE LACK OF STD: CASES OF TAILINGS IN THE SEA FROM BEACH AND RIVER DISPOSAL

5.1 Introduction

There have been many cases of mine waste disposed of in such a way that tailings have eventually reached the sea. The disposal methods were either by direct discharge to a beach or to shallow sea water, or to a river with subsequent flow to the sea. Examples are listed with some descriptions by Ellis (1987, 1988 and 1989). There appear to be others in Indonesia (e.g. Freeport) (Anon, 1992).

The adverse environmental effects from such means of tailings disposal have been well documented in the past. Three cases are summarized here: Marcopper (The Philippines), Bougainville Copper (Papua New Guinea) and Jordan River (Canada). In each case an alternative STD scenario is explored. Such hindsight reviews allow exploration of the principles developed for STD elsewhere, and exploration of limiting factors which will prevent STD from being a suitable means of tailings management. It is also possible to predict in these cases the impact which would have occurred at these sites from STD, and to make a comparison with what actually did happen there.

The principles by which STD was developed at Island Copper in 1970, Kitsault a few years later, and in recent years at Quartz Hill, Alaska, in Papua New Guinea, Peru and Turkey, lead to defining site parameters and tailings characteristics essential if STD is to minimize environmental impact. These defined site parameters can then be used as Screening Criteria for new developments.

The cases described in Vol. I and Chs. 2-4 indicate in principle which site parameters need consideration. They include coastal location, presence of suitable undersea gradients (bathymetry) for generation of a turbidity current flowing to a deep deposition site, and topography on-land for pipeline routing and outfall placement.

It should be noted that tailings onland transport systems currently extend more than 100 km in length (See Atlas, Ch. 4.2). In engineering terms onland tailings pipelines could possibly be constructed far longer. Undersea tailings pipelines have been built to 100 meters depth, and can extend a km or more offshore. Greater depths and distances rapidly become more expensive (See Section 4.4, the Cayeli Bakir Mine).

An example location where a mine is located too far inland in mountainous country to utilize appropriate nearshore bathymetry for STD is the Ok Tedi Mine in Papua New Guinea (Eagle and Higgins, 1988). Figure 5.1.1 shows the mine location some 300 km from the nearest coast, and the course of the Sepik River indicates the presence of mountain barriers to direct coastal access. Hydrographic charts of the coast show water depths of a hundred meters within meters of the shore, with steep slopes to depths greater than a thousand meters.

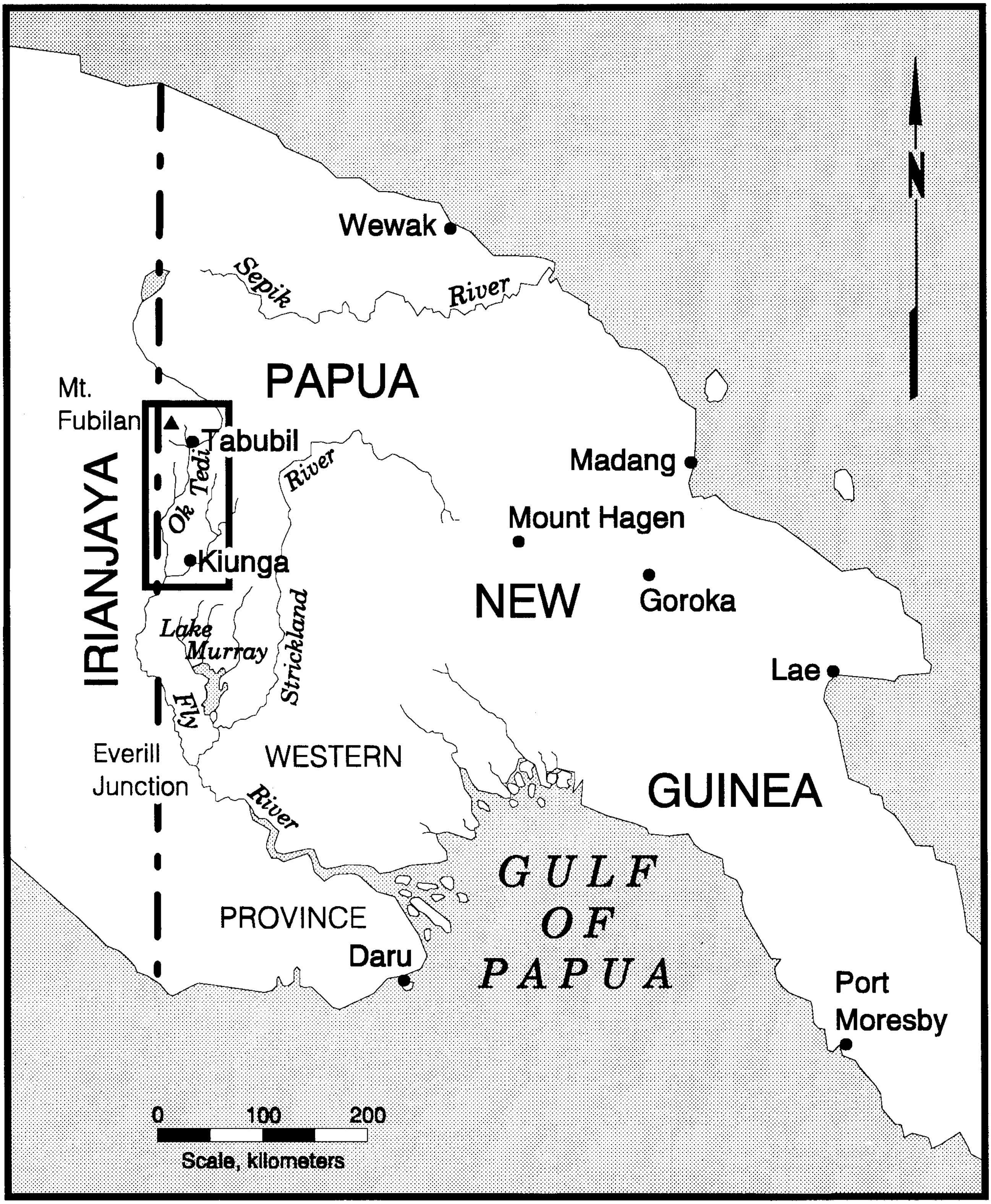

Figure 5.1.1 - Map of the Mainland of Papua New Guinea, Showing Location of the Ok Tedi Minesite near Tabubil (Reprinted and modified from Eagle and Higgins,1988).

Other required site parameters include relatively calm seawater (causing very little dispersion of the tailings density current,) soft bottom depositional areas, little resuspension of tailings after deposition, and finally little upwelling of those particles which do become suspended back into surface waters. The chemistry of the receiving seawater must be such that there is little bioactivation of residual process chemicals and ore trace metals. Finally, if other resources are present they must either not be impacted, or there must be potential for their recovery in ways that are socially acceptable to local people or for compensation for their loss, whether permanent or temporary.

Some limits to these essential site parameters are explored in the cases following.

5.2 Marcopper Mine, the Tapian and San Antonio Developments (The Philippines)

5.2.1 Introduction

Marcopper is yet another low grade (0.4-0.5% Cu), high tonnage (approximately 30,000 tonnes of tailings per day), open-pit copper mine, developed in the late 1960s and early 1970s. It is located in Marinduque Island about 10 km from tidewater, with nearshore deep water being from 15-20 km distant (Figures 5.2.1 and 5.2.2) by other routes.

The mine opted initially to discharge its tailings from the Tapian pit to an onland tailings dump. Then in the early 1970s there was an unusual development in that a second ore-body (The San Antonio development) was found under the onland dump. Consequently a start was made (in the 1980s) on dredging the tailings and discharging to the coast.

Rescan (1989) reports that an STD system was proposed at that time for discharge at Trapichihan Point with suitable nearshore slopes. However a nearshore STD system was installed with discharge at 6 meters depth to a 20 meters deep basin. The shallow slope caused the system to plug and fail within a few weeks of start-up in 1972. The response was to build a causeway by progressively extending beach discharge out to deeper water (Ellis, 1989, Ellis *et al.*, 1981; and see Figures 5.2.3 and 5.2.4).

A review by outside consultants of the environmental information gathered by the mine staff was commissioned by the mine in 1981. The consultants concluded that tailings directly from the Tapian Pit, from the onland dump over the San Antonio orebody, and eventually from the San Antonio development should be considered as a single continuing waste stream for the 20-30 year life-time of the twin mines. They recommended a new feasibility investigation for deep submarine disposal of the finest tailings fraction (slimes). These should be separated in the milling process from the coarse fraction, which would be backfilled to the Tapian pit. The STD site recommended was again Trapichihan Point. The consultants emphasizedd that an alternative plan for a shoreline tailings dump should be dropped, due to its risk of acid waste generation, catastrophic collapse during earthquakes, and social impact.

Local objections to the Marcopper mine, supported by international environmental groups (McAllister 1987; Velasquez 1987), publicly surfaced during the political upheavals surrounding President Marcos in the late 1980s. The mine was closed for a few months in 1988.

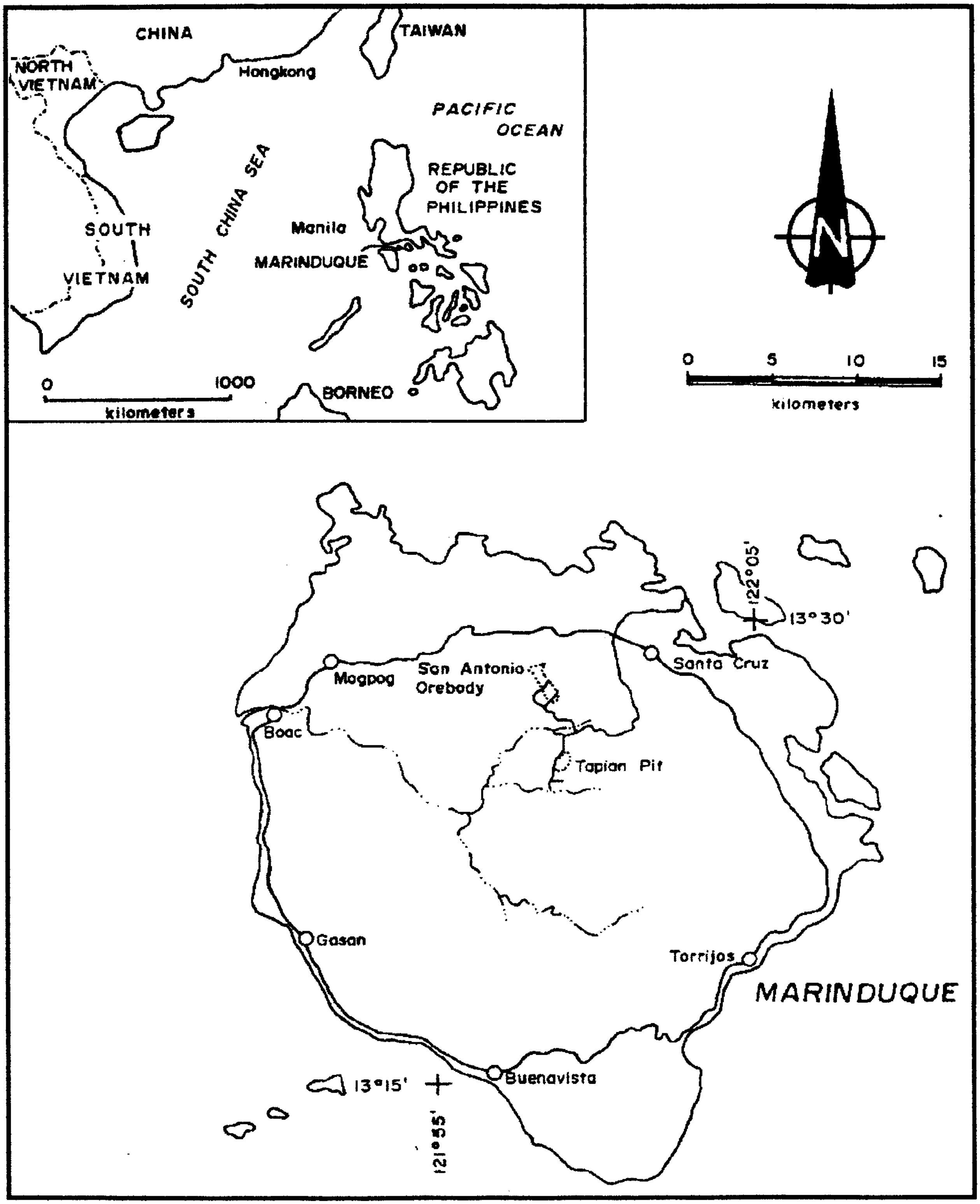

Figure 5.2.1 - Map Showing Location for the Marcopper Mines (Reprinted and modified from Rescan, 1989).

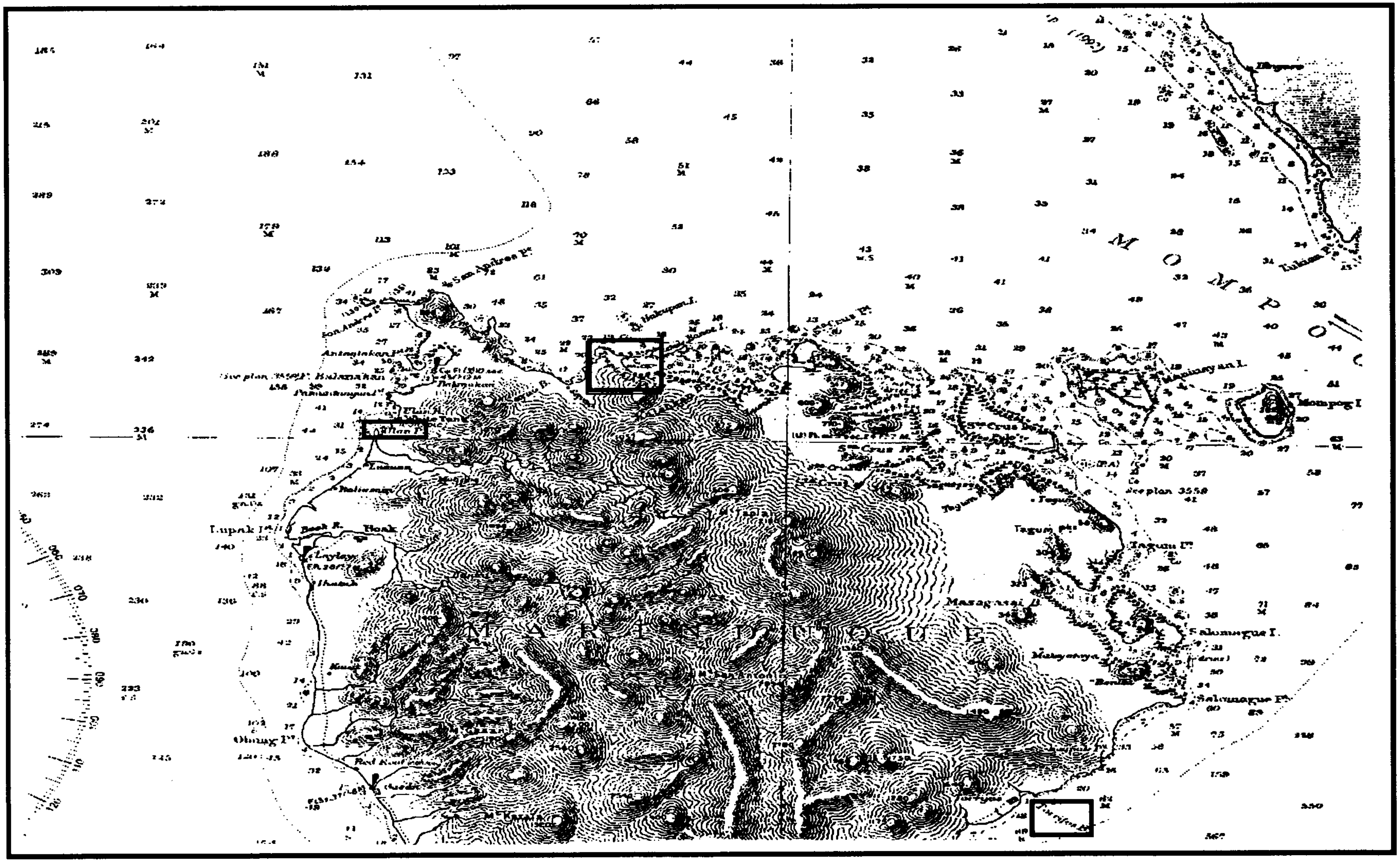

Figure 5.2.2 - Coastal Bathymetry for Marinduque Island (Reprinted and modified from Admiralty Chart 3817). The 3 boxed areas are potential STD sites (see Section 5.2.3).

Figure 5.2.3 - The Tailings Causeway for the Marcopper Mines and Surface Turbidity in 1981.

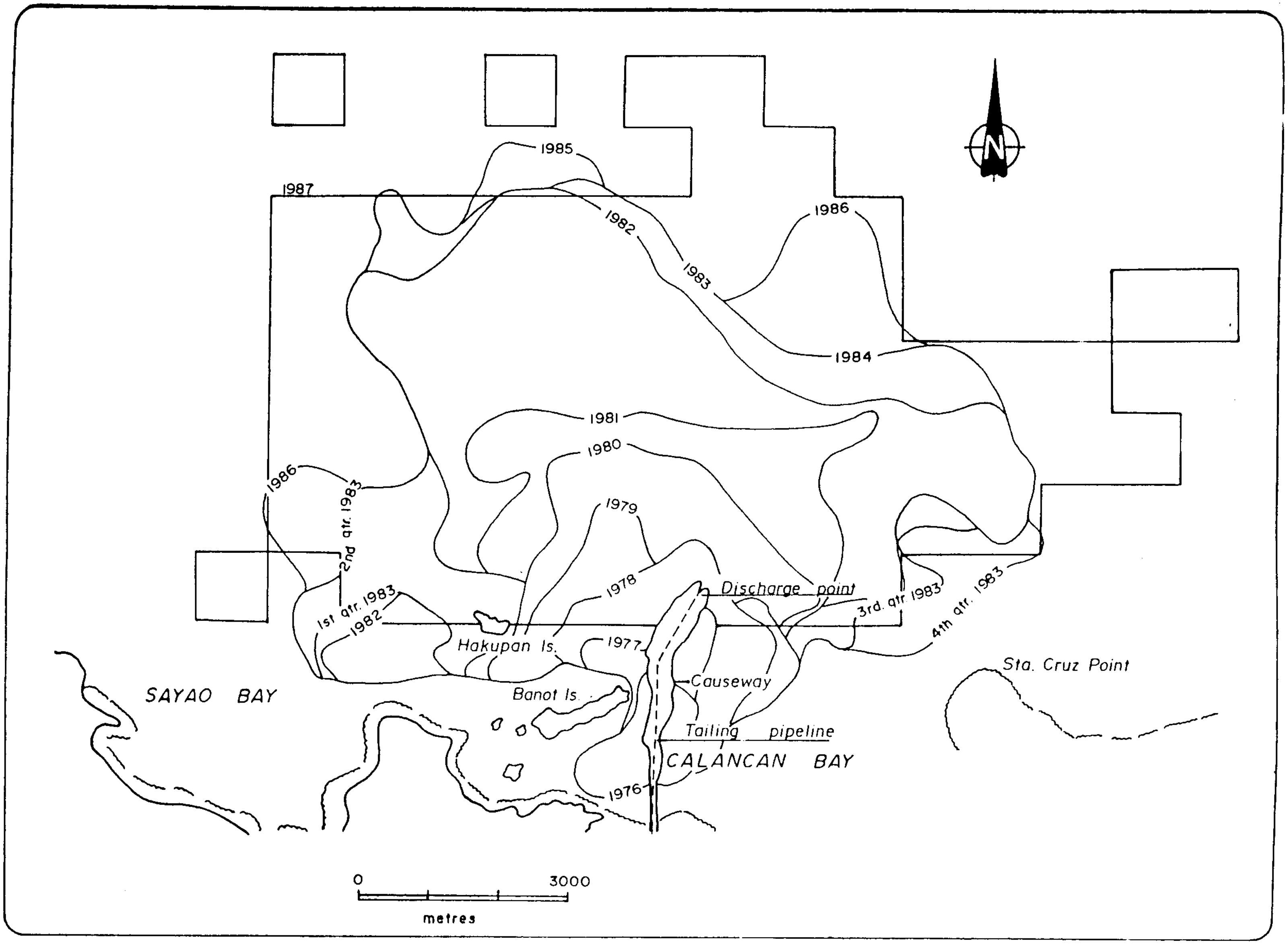

Figure 5.2.4 - Extent of Tailings Coverage Yearly from 1976 to 1987 from the Marcopper Mines (Reprinted and modified from Rescan, 1989).

An Environmental Impact Statement for the second pit, the San Antonio development, was prepared in 1989 (Rescan, 1989). This was based on the concept of STD for the fine fraction tailings (<50um).

5.2.2 The Mine and Its Environmental Impact

The mine is located in north central Marinduque Island (Figure 5.2.2) from 8-12 km from the nearest shoreline, in Calancan Bay. The Tapian pit lies about 4 km south of the San Antonio development. Geological ore reserve studies indicate reserves of approximately 200 Mt at 0.44% copper with subsidiary gold and silver.

> Copper mineralization at the San Antonio development is hosted in a medium-grained porphyritic hornblende diorite, located within the northwesterly-trending tectonically-active Philippine Mobile Rift Zone. The primary copper sulfide mineralization, consisting of chalcopyrite and minor amounts of bornite, occurs mainly as fracture-filling and disseminations within the medium-grained host rock, a near-surface supergene enriched chalcocite zone is locally developed. (Rescan, 1989)

The proposed beneficiation process as described by Rescan (1989) consisted of a "..primary crushing facility, a semiautogenous grinding (SAG) circuit, sand and slime flotation circuits, conventional three-stage cleaning, dewatering and combined land and marine disposal." Ore would be processed at a maximum rate of 30,000 t/d. A simplified process flowsheet is shown in Figure 5.2.5.

Bathymetry and tailings deposition to 1987 are shown in Figure 5.2.4. Monitoring routinely covered tailings deposition, plus some biological/fishery surveys by scuba diver, and surveys for trace metal contamination.

There appears to have been no formal community involvement initially, although there has been growing informal action, assisted by international agencies (McAllister 1987, Velasquez 1987). The latter document clearly shows local hostility generated to that time.

By 1989, Marcopper had commissioned a detailed EIA (Rescan, 1989) for the San Antonio development and STD (Figure 5.2.6). The recommendation supported previous concepts of backfilling the coarse tailing fraction to the Tapian pit, and STD for the fine fractions (<50um). The proposal called for a deaeration chamber 4.2 km offshore (at the end of the causeway pipeline) with a submarine pipeline to 40 meters depth 1 km further offshore. The discharge would be to a slope of minimum 5% for 300 meters distance. This slope was needed to prevent blockage from settling of the coarsest fraction. An incised channel would receive the finer fraction density current and conduct the tailings to a broad area below 100 meters depth approximately 5 km westwards (Figures 5.2.6 and 5.2.7)

The environmental impact of the shallow-water tailings discharge to Calancan Bay was summarized by Rescan (1989). The causeway creates a major block to natural current flows. There is surface turbidity and deposition of tailings. The latter will have had substantial effects on coral and mud bottom ecosystems, only the former of which had been documented to any extent (by scuba surveys). There has been some documentation of recovering nearshore

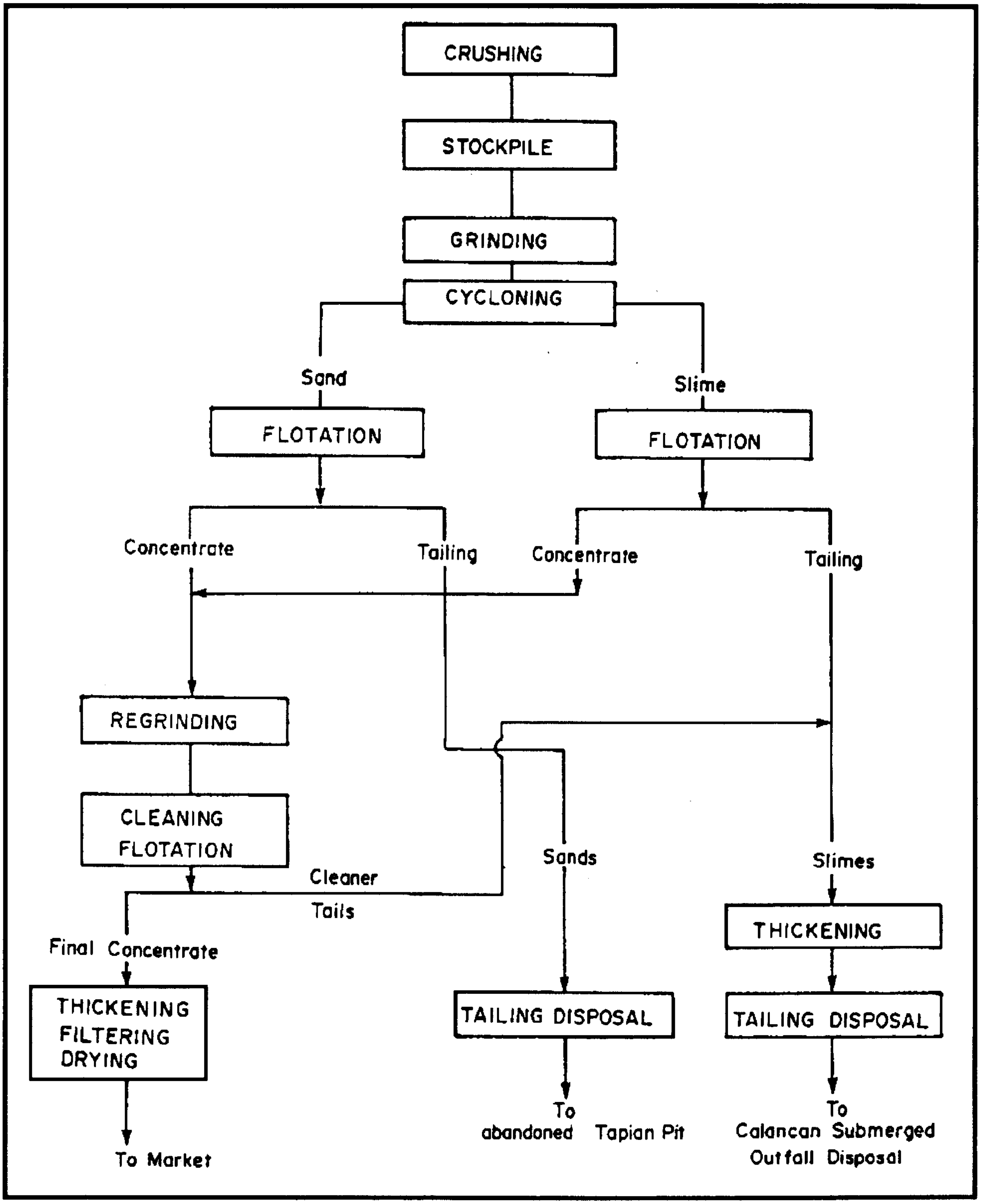

Figure 5.2.5 - Simplified Process Flow Sheet for the Marcopper Mines (Reprinted and modified from Rescan, 1989).

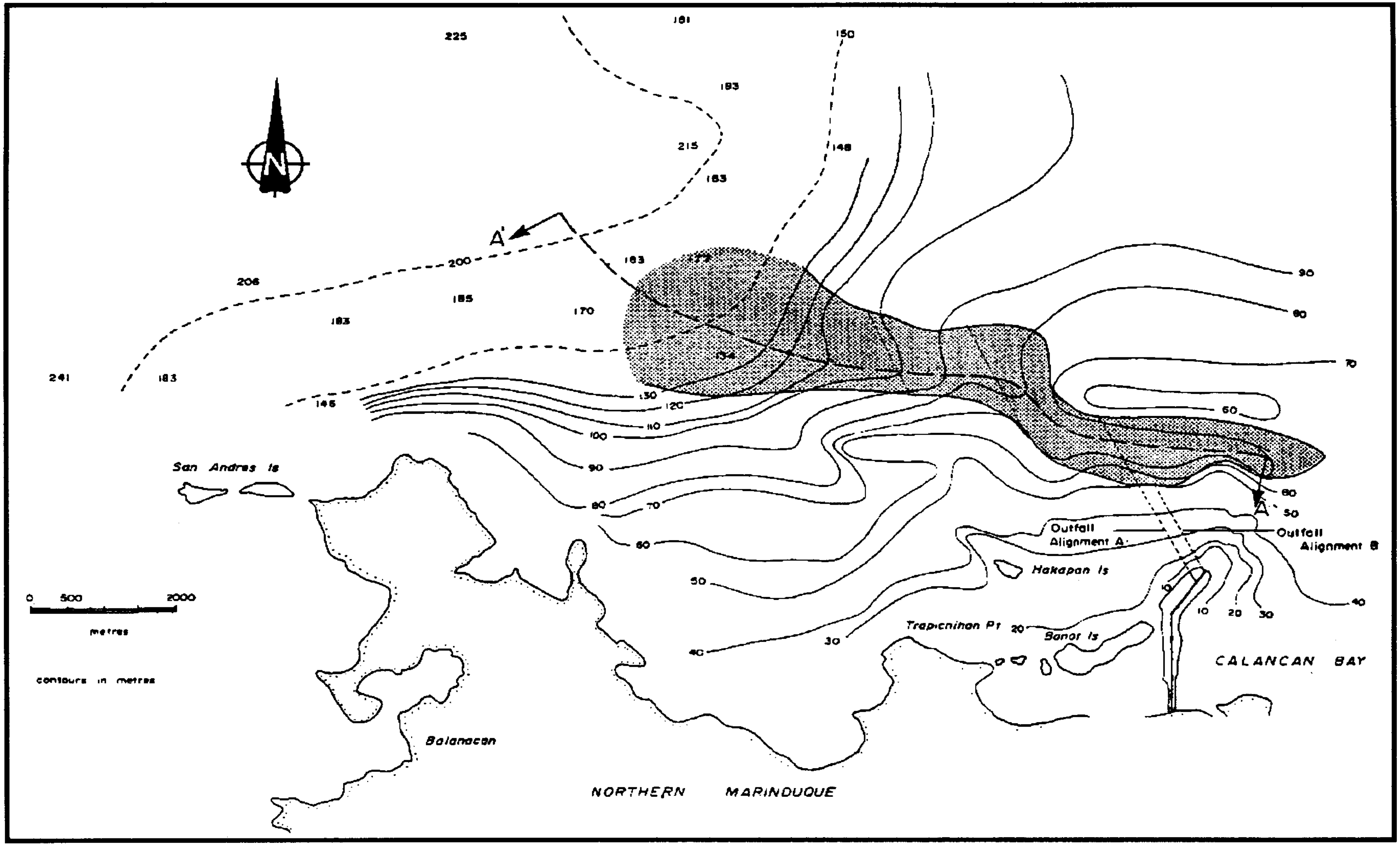

Figure 5.2.6 - Predicted Deposition of Tailings Slimes for the Proposed STD from Marcopper Mines (Reprinted and modified from Rescan, 1989). A-A' represents the thalweg.

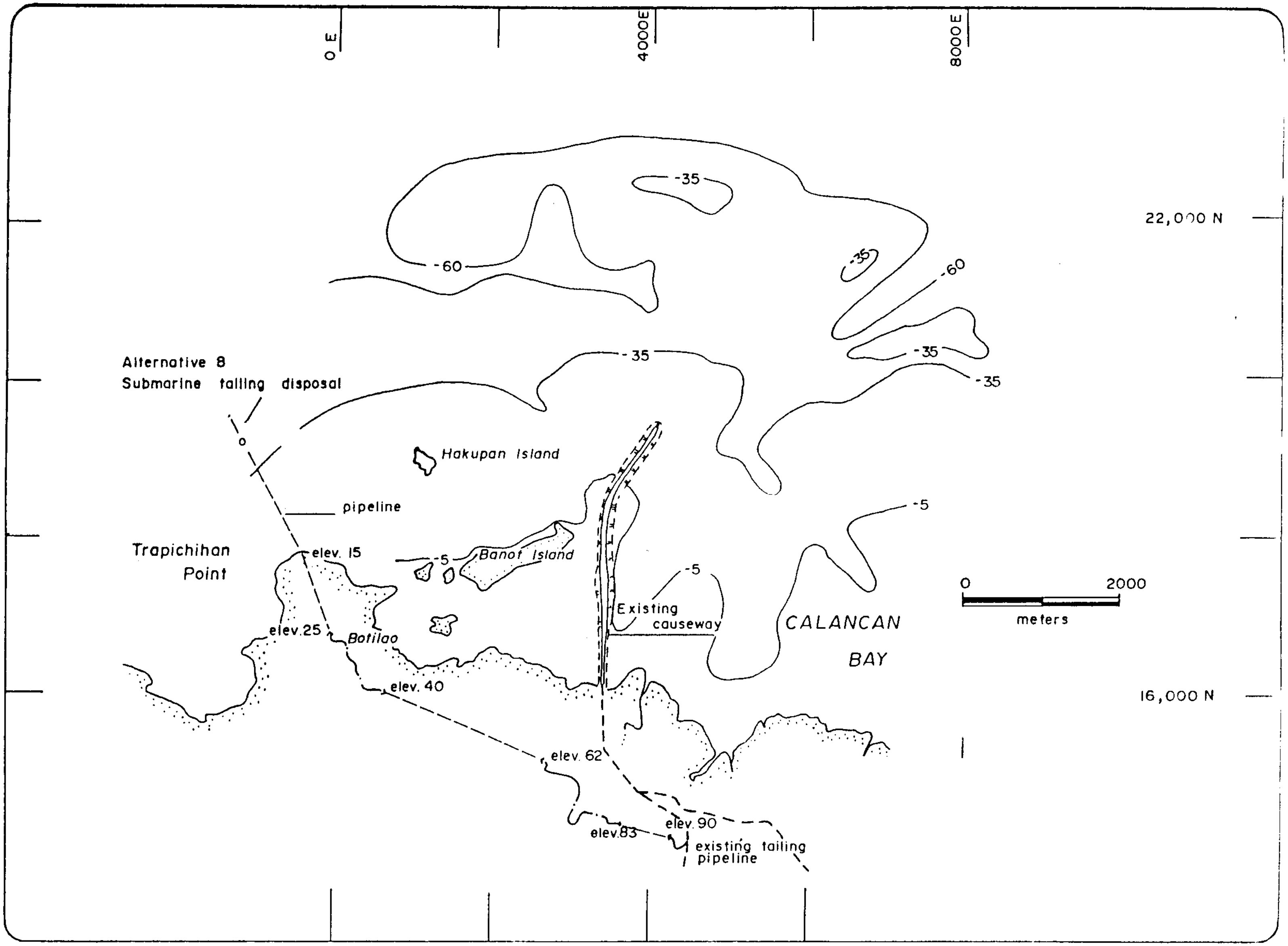

Figure 5.2.7 - Potential Site for STD from Marcopper Mines at Trapichihan Point (Reprinted and modified from Rescan, 1989).

ecosystems in recent years (*i.e.* Trono, 1988) as the causeway has been progressively extended, and more of the tailings are swept offshore. Impact on fisheries cannot be determined, due to heavy fishing (some with destructive methods such as dynamite and cyanide) in the area, including immediately by the tailings plume. Trace metal contamination was generally slight, although oysters nearby have been detected with copper and zinc at levels of concern for human consumption (e.g. copper 1950 ppm and zinc 1310 ppm dry weight). There has been a reclamation program implemented on the causeway to control fugitive dust.

Rescan (1989) also noted the development of environmental monitoring. At that time monitoring had been extended from initial occasional marine biological surveys by scuba diver to a routine program. This consisted of monitoring chemistry of the tailings discharge and seawater, surveying local fisheries for yields and trace metals, monitoring tailings deposition by grab samples of the seabed, surveying the biodiversity of intertidal and subtidal biota, and bioassaying the effluent with Tilapia and milkfish.

In summary, the Marcopper Mine was developed initially with little environmental information and community involvement. Gradually the scope of EIA was widened, and tailings disposal adjustments made. In the 1980s political conditions and social responses to the mine culminated in a temporary closure. By that time the mine had twice sought engineering and environmental recommendations for tailings disposal by STD, but had not implemented the recommendations received.

5.2.3 The Potential for STD

STD has been identified for the Marcopper operations based on extension of the existing surface tailing disposal system. The causeway has already been extended to a distance offshore where it was sufficiently close to a potential STD site that engineering was practical. Environmental consequences, if STD were implemented, would be an improvement over those generated from the surface tailings disposal through the 1970s and 1980s.

Although the site for STD has been identified based on the prior disposal system, there are alternative sites available.

The existing onland tailings line could have been extended a further 2 km westward to Trapichihan Point where a steep gradient exists at the shore (Figures 5.2.6 and 5.2.7). The slope descends steeply to about 45 meters and then becomes gentler. Use of this site would have required negotiations with owners and users of land over a further 2 km.

Marinduque is an island of maximum dimension only about 50 km. Potentially any nearshore deep water site should be suitable for STD. Rescan (1989 identified one at Torrijos Bay 20 km distant on the east coast with 50 meters depth water within 1 km of shore (Figure 5.2.2). Similar depths and distances would be involved to the west down the Ulan river to Ulan Point. Both sites would have required negotiations with land owners and users over an even longer distance than for Trapichihan Point, as well as having substantially greater costs.

5.3 Bougainville Copper Mine (Papua New Guinea)

5.3.1 Introduction

Bougainville Copper Mine (BCM) provides a case where a very large (and initially very profitable) open pit operation, with river disposal of tailings, coincided (1970s through the 1980s) with social disruption, eventual regional anarchy and loss of central government control, mine closure (in part because of danger to personnel), and write-off by the multinational corporation involved.

There is continuing discussion about the cause and effect relationships between mining, social impact and political instability, especially in the nearby nations of the Solomon Islands and Fiji with mining potential (*i.e.* Kabutaulaka 1993; Wasi 1993). No-one wants another Bougainville.

5.3.2 The Mine and Its Environmental Impact

The mine is located inland, about 20 km from the east coast and 25 km from the west coast (Figure 5.3.1) of the island. It is at 670 meters elevation, within 3 km of the watershed divide between east and west flowing rivers. It is approached by road from the east coast (Figure 5.3.2). This was built specifically for mine access, and required its own set of land use negotiations (AGA 1989) independent of those for the mine area and the tailings route. The access road allowance also accommodated a concentrator slurry pipeline to the coast.

The mine is in steep, rugged highlands, supporting tropical rain forest with 4400 mm rain a year. There were some tribal people inhabiting the area, and denser populations on both the eastern and western coastal strips. Residents have strong traditional rights over land ownership, use and inheritance. Even the initial prospecting generated some social conflict over land access.

The mine is described in AGA.

> The Panguna ore body is roughly elliptical in shape and occupies and area approximately 2500 meters by 1000 meters to a depth of 300 meters beneath the Kawerong Valley near its source. The deposit, as originally defined, comprised 950 million tonnes of ore grading 0.48% copper and 0.55 grams per tonne gold, about 3 grams per tonne silver and a trace of molybdenum....The mine is a roughly symmetrical, cone-shaped excavation or open pit with benches stepping down from the lip... (it) is approximately 2.5 km across and 350 meters deep...Each day approximately 300,000 tonnes of ore and waste are blasted, excavated and trucked from the pit...
>
> The ore is selectively mined. Ore with disseminated copper is crushed for direct delivery to the mill and ore with copper in joints and fractures is upgraded in the pre-concentration and screening plants (PCS). The ore at this stage contain 3% copper sulphides and 0.5 to 10% iron sulphides.... Flotation cells.. stimulate frothing which selectively removes the copper sulphides on bubble surfaces. Gold and molybdenum are collected with the copper sulphides and are not separately removed. (1989)

Tailings (130,000 tons per day) were discharged to the Kawerong River, by pipeline terminating below the waste rock dump. The tailings then flowed into the Jaba River (Fig 5.3.3), and across

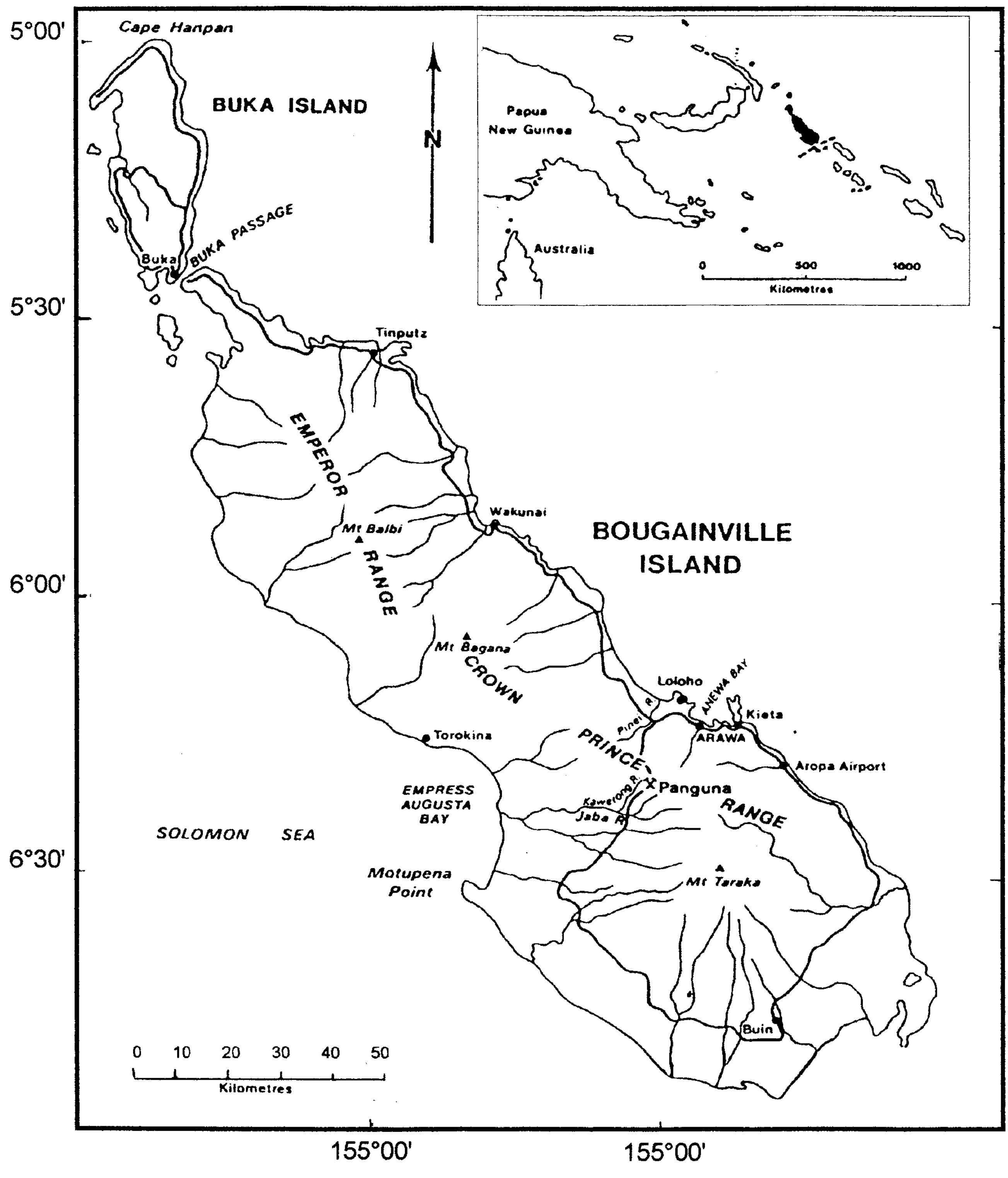

Figure 5.3.1 - Map of Bougainville Island Showing Location of the Mine (Reprinted and modified from AGA, 1989).

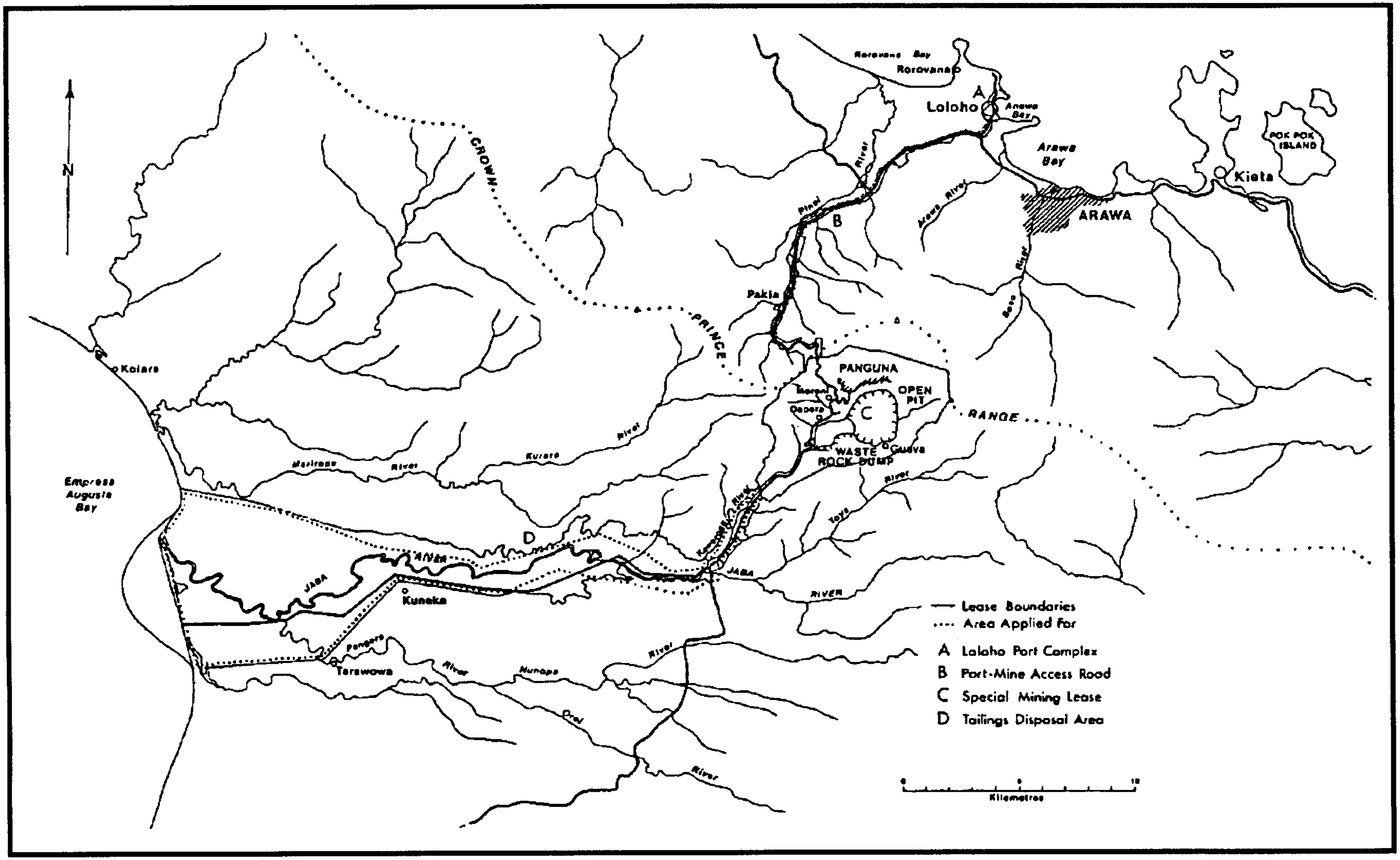

Figure 5.3.2 - Arrangement of Bougainville Copper Mining Operations (Reprinted and modified from AGA, 1989).

Figure 5.3.3 - Tailings Stream Filling the Kawerong Valley downstream from the Bougainville Mine and Depositing at the Junction with the Jaba River.

the coastal plain where they partially silted out in two major basins (Figure 5.3.4). The remaining tailings eventually reached the sea in the shallow Empress Augusta Bay (maximum depth to about 60 meters - Ellis, 1984, 1989 - Figures 5.3.5 and 5.3.6), and formed an extensive delta. Effectively the two rivers had been converted into a tailings flume, unconfined and flooding over the coastal plain during and after the frequent storms.

An extensive environmental monitoring program was developed during the mine's lifetime (Ellis, 1989), although initially monitoring appeared to be directed at establishing compensation values for lost resources, largely river fisheries. There had been little marine environmental information available prior to operations. By 1989 AGA were able to report that monitoring encompassed hydrometeorology, sediment transport, chemical and biological monitoring and revegetation investigations. Monitoring extended into the marine ecosystems on both coasts.

BCM environmental staff and consultants developed a number of predictive models concerning sediment deposition and trace metal leaching. These allowed selection, in the late 1980s, of an upgraded tailings disposal system from several possible options. By 1989 a tailings pipeline from the mine to the west coast at the existing tailings-derived delta on the west coast was under construction. It had been recognized that the tailings already deposited on land caused severe, and lasting, environmental problems - 600 years was one estimate for continued leaching from the waste rock dump. AGA (1989) stated "Stabilization of the area may take tens of years, rehabilitation much longer".

There is an unremarked possible consequence of the upgraded tailings system extending the existing delta into Empress Augusta Bay. The extended delta, with substantial air and aerated shallow water exposure, would, according to the MEND information (See Section 1.2) largely transfer the risk of trace toxin leaching from onland to the coast.

Initial community hostility to the original prospecting gave way to formal local community involvement as subsistance residents realised that their livelihood from vegetable gardens, and fisheries in the Kawerang, Jaba, Pangara and other rivers had been destroyed. There have been substantial relocation and compensation payments made during the mine lifetime (AGA 1989). AGA lists stated concerns ranging from inadequate forewarning of substantial environmental losses and inadequate compensation to corruption in administration of the Trust Fund and health problems.

There is also an underlying belief in *kago*: "...the efficacy of supernatural assistance for the acquisition of material goods" (Oliver, 1981). In short there were substantial differences in perceptions and understanding between the mining company and land owners and users. These misunderstandings encompassed land use, the meaning of land alienation for mining, the value of compensation, and the eventual return of land.

On January 7, 1990 the mine started a retrenchment program. By March 24 1990, BCM had withdrawn its employees from the mine site. Although it was able to protect its resources in the coastal towns at that time, the mine site was abandoned "as a result of militant activity" (RTZ 1990). It is difficult to keep track of the political situation, but there is a secessionist movement on Bougainville Island which is being constrained by the PNG government (Kabutaulaka, 1993; Wasi, 1993).

Figure 5.3.4 - Tailings from the Bougainville Mine Filling the Channel of the Jaba River and Flowing to the West Coast. Tailings Deposition from Flooding is being Reclaimed.

Figure 5.3.5 - Tailings from the Bougainville Mine form a Delta in Empress Augusta Bay after flowing down the Jaba River.

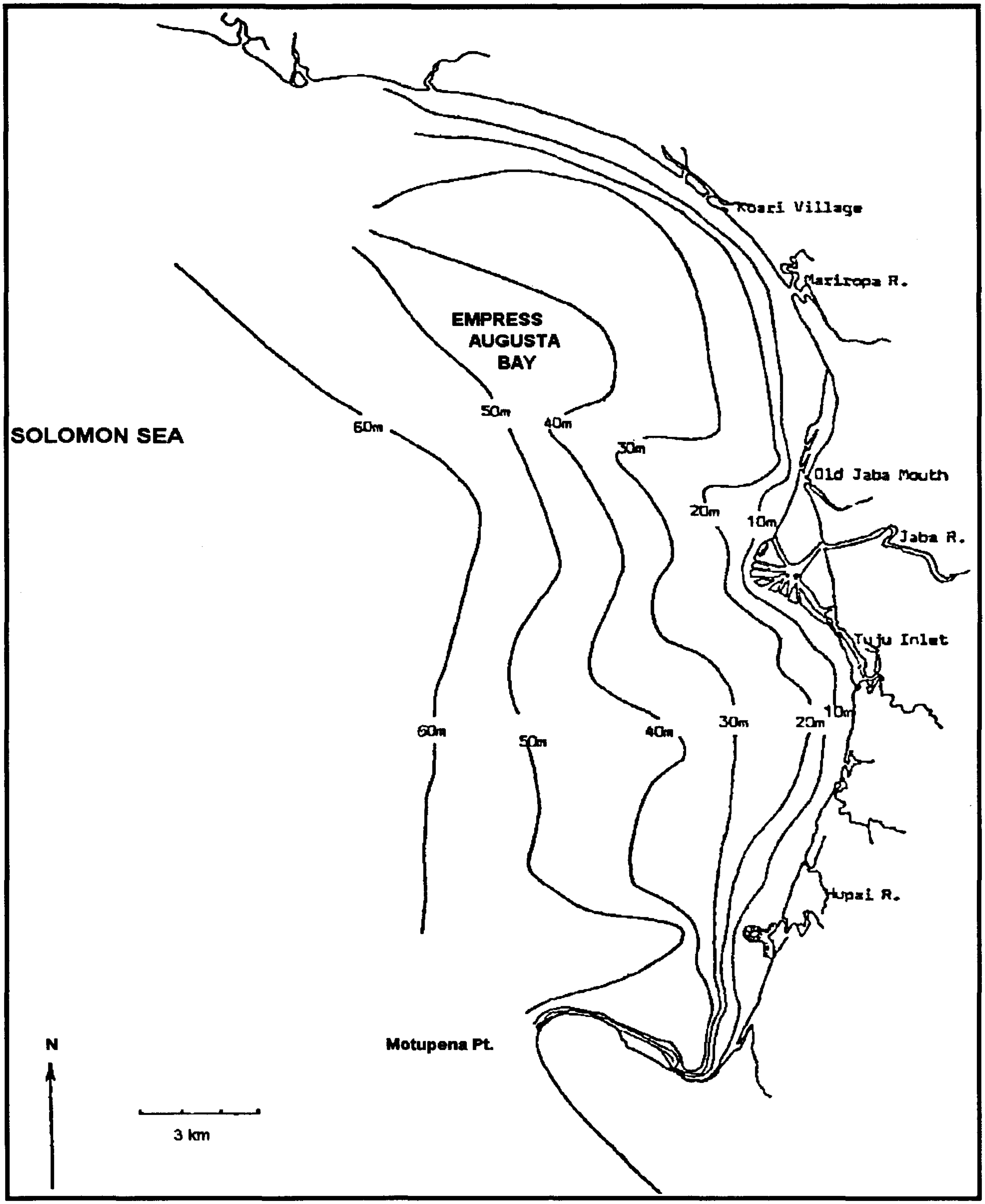

Figure 5.3.6 - Bathymetry of Empress Augusta Bay which receives the tailings from the Bougainville Mine (Reprinted and modified from Powell, 1984).

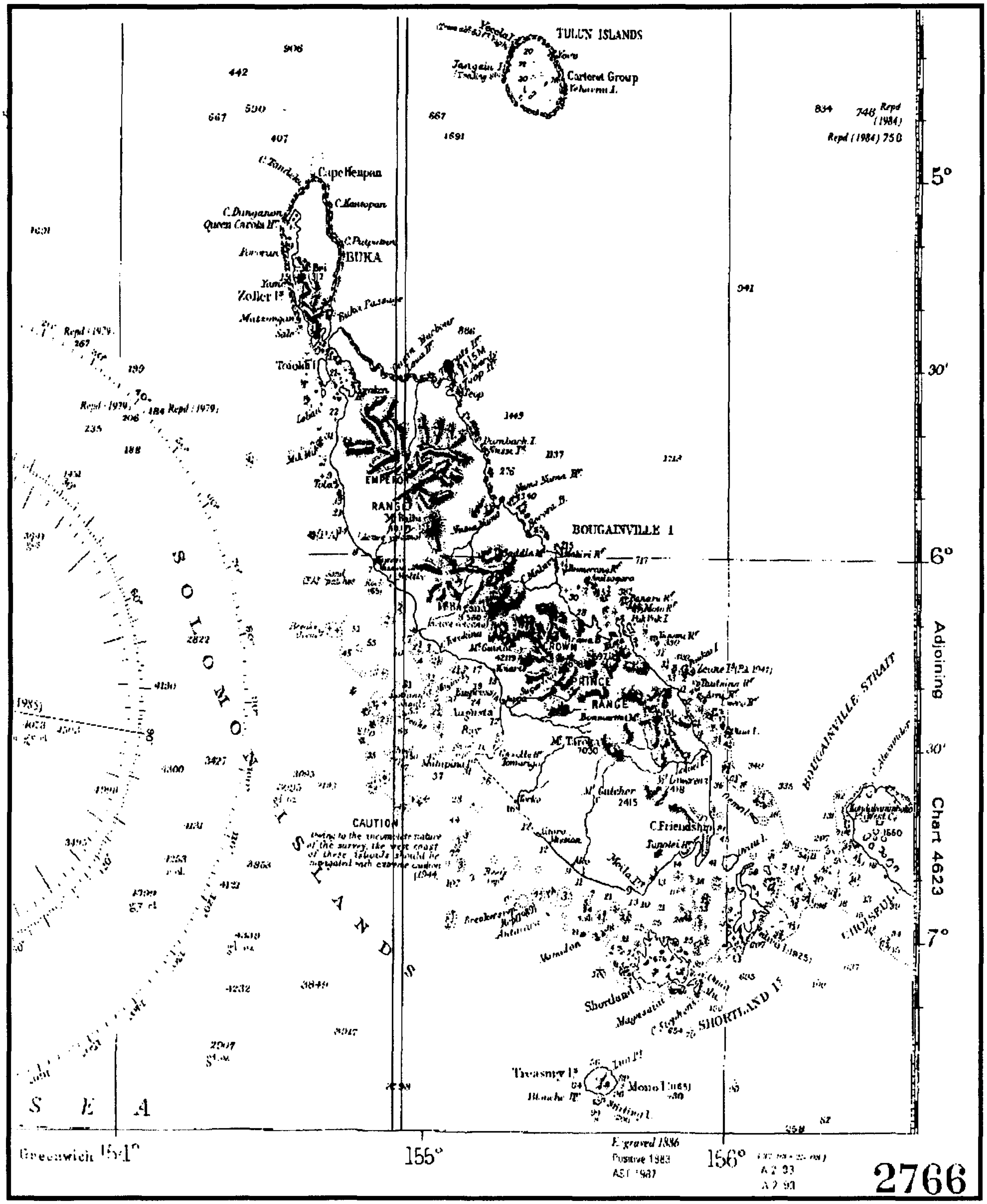

Figure 5.3.7 - Coastal Bathymetry around Bougainville Island (Reprinted and modified from Admiralty Chart 2766).

In summary, BCM originally discharged its tailings to a river system some 25 km from the sea. Tailings deposited enroute and at the coast, and caused considerable social disruption. There was growing local demand to compensate residents for lost subsistance livelihood. By 1990, BCM was developing an onland pipeline to transport tailings onto the delta already formed. The delta would then prograde out to sea within the shallow Empress Augusta Bay (a silled bay with maximum depth of 30 fathoms). The mine was abandoned in 1990, due to "militant activity".

5.3.3 The Potential for STD

Figure 5.2.7 shows that the closest available area for STD is on the east coast near Kieta. Along this coast a fringing reef from 1 - 5 km offshore marks the line of steep drop-off to several hundred meters depth.

The concentrator slurry pipeline is within the road allowance, so potentially a tailings line could be installed there also. The slurry line uses a pump to pass the watershed divide, whereas a tailings line would need a tunnel.

These requirements for onland tailings transport are within those accepted at other mines, e.g. Atlas Copper (See Section 4.2).

The west coast, to which much of the tailings were discharged by river transport, is more distant than the east coast (40 kms down the Kawerong/Jaba river, and the deep eventual dropoff also more distant offshore (approximately 15 nautical miles) than on the east coast).

Empress Augusta Bay is a basin with limited, even if large, capacity for a tailings stream. Also the gentle slope of Empress Augusta Bay, (*i.e.* 1 km for each 10 meters depth out to 60 meters) (Figure 5.3.3), might be suitable for STD, but in principle is less attractive than the nearshore steep drop off to great depth on the east coast.

Adopting east-coast STD at the time of mine development would have meant that the eastward impact would have been accentuated to some extent by adding construction of a second pipeline to that of the slurry line and the road. Negotiations would also have been needed with landowners and landusers at the coast for an outfall site, with some pre-emption of land. However, the environmentally and socially far-reaching impact on the west coast could have been reduced to negligible levels; and could have been constrained to the upper levels of the Kawerong river. On the east coast in contrast, design and construction of an STD outfall would not have imposed significant impact in the shallow water of the lagoon.

An environmentally sound STD system is dependent on there being adequate environmental knowledge and the potential to make appropriate social arrangements. It would have been very difficult to obtain these from the technical and social procedures available in the late 1960s and early 1970s. Misima mine (Ch. 2) shows that they are now possible.

In principle, the Bougainville mine meets requirements for STD in terms of proximity to a coast with suitable bathymetry.

5.4 Jordan River Copper Mine (Canada)

5.4.1 Introduction

The small underground Jordan River Copper Mine is set back about 2 km from the coast in south Vancouver Island (Figure 5.4.1). Its quoted discharge rate of 100,000 IGPD of tailings converts to approximately 450 m^3/day. The mine was permitted to discharge its tailings by shallow discharge to a wave-exposed, high-energy, gently sloping nearshore shelf. The outfall was poorly located, designed and constructed. It broke at least twice (Figure 5.4.2), and apparently more frequently but unreported (Elder, 1973). The causes for failures of outfall systems need to be considered in planning new STD systems.

5.4.2 The Mine and Its Environmental Impact

The mine was re-opened in April 1972 after three prior short periods of operation, starting in 1962, by different operating companies and funding sources. Marine tailings disposal was terminated in December 1974 when the funding company placed the mine in receivership with an accumulated $2,000,000 debt (Bridges, 1978).

In 1962 reserves were evaluated as approximately 1 meters tons of 1.54% copper, and approximately 750,000 tons of 1.14% copper. The mill was placed underground and the tailings were pumped through a 15 cm line to the tidewater, presumably at Outfall Point (Figure 5.4.2). Initially the tailings were the consistency of very fine sand, with 79.4% particles less than 0.074 mm, 11.2% $\geq$0.074 and $<$ 0.10 mm; and 8.5% $\geq$0.10 and $<$ 0.15 mm.

Mine flooding was a constant problem during operations. It was the cause of several temporary interruptions and the first (1963) closure. In part, flooding was the result of insufficient geological knowledge or insufficient perception of risk by the operator in charge (Titus, 1978).

In 1972 a new 20 cm diameter high density polyethylene pipe tailings line was installed to meet a 12 meters discharge depth requirement set by the regulatory agency. The terminus, approximately 1 km offshore, was intended to discharge to a depression within Juan de Fuca Strait (Figure 5.4.2). After the failure of several attempts to bury the pipeline in a backhoe-excavated trench, the pipe was simply laid over the high energy beach and sub-tidal shelf, anchored by concrete blocks.

The tailings line suffered one crisis after another, as there were engineering difficulties in installing the tailings line across the high energy shelf. The line plugged and broke the first time after only a few days of operation. A temporary permit allowed near-beach discharge while a new tailings disposal system was designed. Meanwhile the mine was brought to court (and fined) on a charge of releasing tailings to the river (the emergency tailings pond overflowed during a rainstorm). The final closure of the mine in 1974 was in part brought about by the cost implications of maintaining the discharge point inititally required by the regulatory agency and, later confirmed after application for a change.

The 1972 mill grind was also a very fine sand with 9.5% coarser than sieve # 100, 46.4% between sieve # 100 and 230, with the balance finer. Only 50-75% of the tailings were

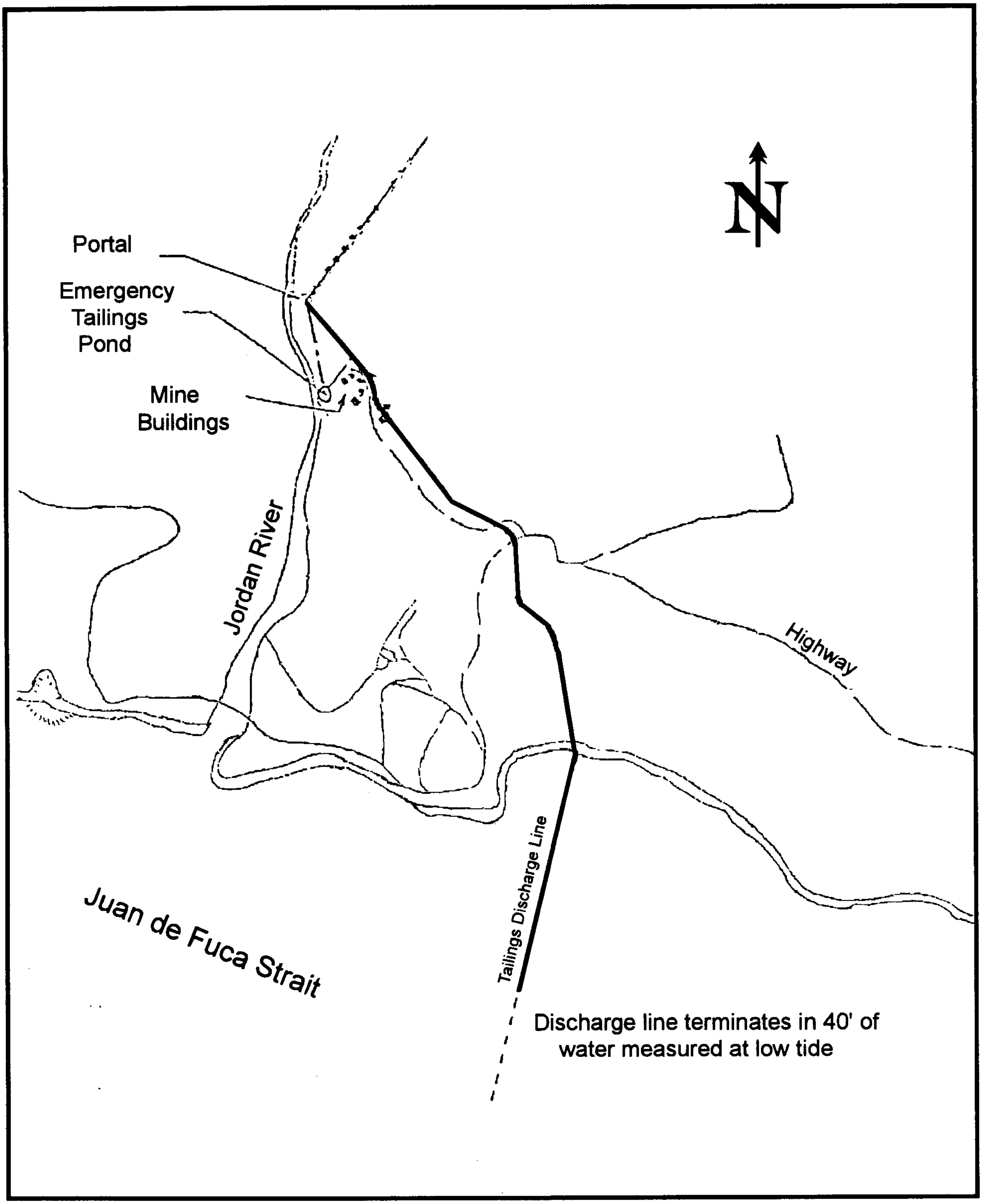

Figure 5.4.1 - Map of the Mine Layout at Jordan River (Reprinted and modified from Venables, 1973).

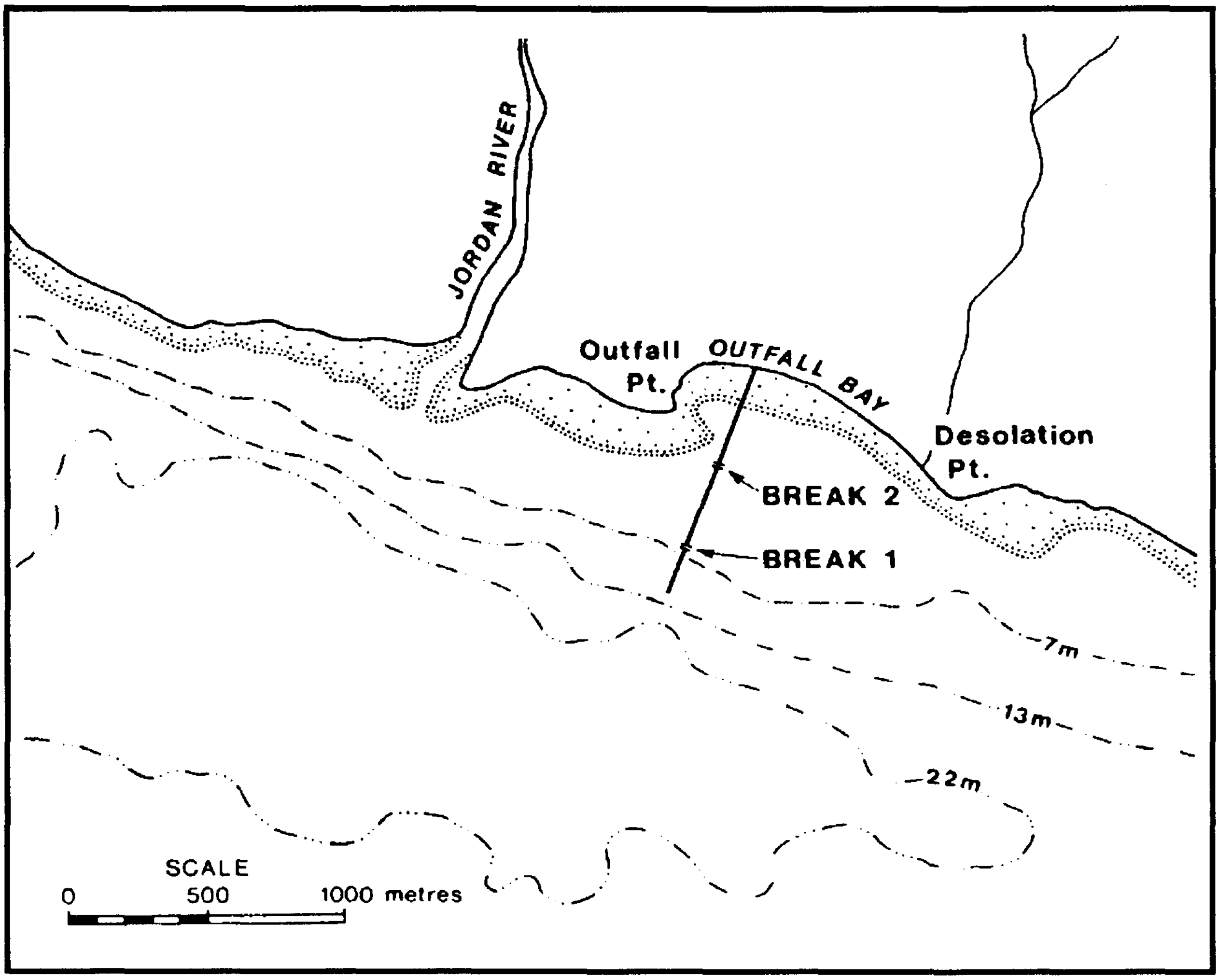

Figure 5.4.2 - Positions of Two Documented Breaks in the Shallow Water Tailings Outfall of the Jordan River Mine (Reprinted and modified from Ellis, 1980).

estimated to deposit, with the balance suspended and dispersing (Littlepage, 1973). Figure 5.4.3 shows a surface plume from the original terminus, and Figure 5.4.4 an onshore drifting plume from a nearer-shore breakpoint. The latter was the discharge point from soon after operations started to closure, for about a year and a half.

A marine monitoring program had been designed, but the sampling stations, based on the original discharge point, became irrelevant after the first break (Ellis 1975a & b). Progressive postponement of monitoring for the outfall to be replaced meant that little monitoring was achieved during the first year of operations. Finally by closure it was determined that copper levels were higher near the outfall (250 - 1510 ppm) than at a reference site (15-16 ppm) 25 km down the longshore current to the east, but no higher than prior to discharge in 1972 (Ellis 1977; and Ellis and Popham, 1983). The high levels appeared to be from prior operations. Nevertheless by 1978 sediment copper levels had increased (70-100 ppm) at the reference station (Meidinger, 1978), presumably from longshore drift of the beach tailings deposits.

A similar conclusion was developed by Kilby (1991) in a detailed geomorphological analysis of nearshore sediments along the north shore of the Straits of Juan de Fuca (Figure 5.4.5). Longshore drift and wave-action had formed a nearshore placer deposit (out to 800 m) with high heavy metal concentrations ($>15\%$ by weight), including Cu, Fe, Ti, Cr, V and Mn, with some Ni and Co. The latter were apparently derived from the ball mill, and the others from the orebody. The placer extended from Outfall Point along the length of Sandcut Beach.

After the tailings line broke and discharged in effect on shore, the breakpoint with discharge upwelling through the surrounding tailings was exposed at very low spring tides, and created a safety hazard.

The extended smothering effect on local algal beds and rocky shore organisms had however recovered by 1975. These are species which naturally are adapted to frequent high turbidities from storm river runoff.

At the time of mine development in the early 1970s, local attitudes towards the mine were mixed. There was formal opposition by environmentally concerned citizens (Elder, 1973), but a subsequent survey (Titus, 1978) stated that the main complaint about previous mining operations was that miners left without paying their bar bills.

In summary, Jordan River Mine was permitted to discharge its tailings at 12 meters depth over a high energy beach and wave-swept platform. The 20 cm pipeline, anchored with concrete blocks was inadequate and broke several times. For most of the 1972/4 operational period, tailings were discharged from the broken end at low tide level. There was consequent copper contamination of the beach, and temporary biological impact.

5.4.3 The Potential for STD

The bathymetry in Figures 5.4.2 and 5.4.5 shows that there is no steep dropoff nearshore. There is a depression within accessible distance, but calculations using 1973 procedures indicated only 50-75% deposition potential with the fine grind used in the mill. New formulae for modeling tailings density current behaviour (as developed for Quartz Hill and Island Copper (Volume I)

Figure 5.4.3 - A Surface Plume of Tailings from the Jordan River Mine close to the Intended Discharge Point.

Figure 5.4.4 - Surface Plume of Tailings from the Jordan River Mine at the Final Break Point Drifts back onto Shore.

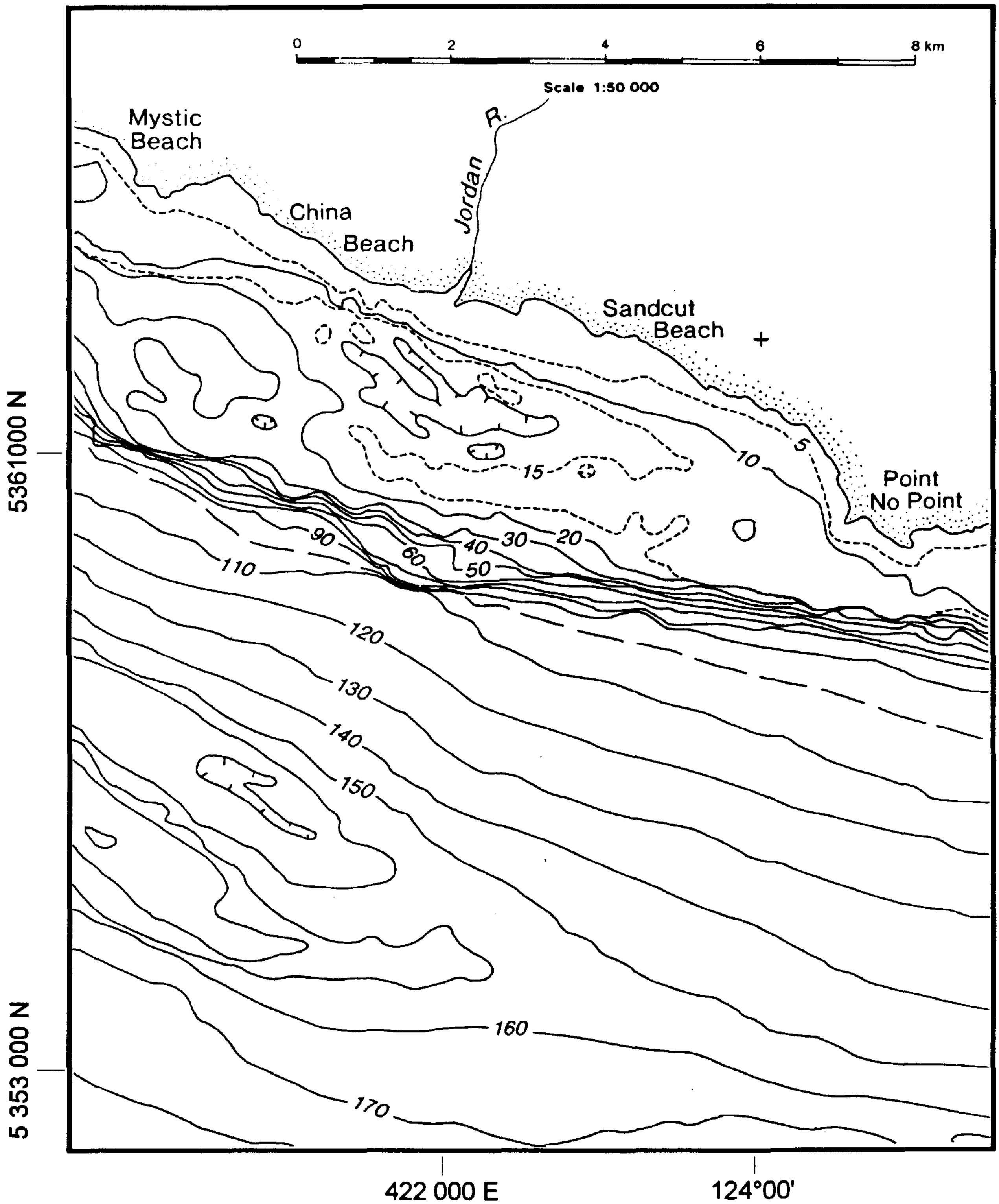

Figure 5.4.5 - Offshore Bathymetry in Juan de Fuca Strait near the Jordan River Mine (Reprinted and modified from Kilby, 1991).

and the STD in Peru (Section 4.5)) would provide better predictions than were available then. These would need to be used if the mine were to re-open, and STD was considered an option for tailings disposal.

This modeling in turn would require considerable physical and sedimentological oceanographic surveys for input data. The state of such modeling appears now able to give reasonable predictions for slope gradients required to generate density current flow away from the end of the pipe thus preventing blocking.

STD is a possible option for tailings disposal at this site, but considerable data gathering and analysis is needed to verify whether a proposal for STD should be adopted or rejected.

6.0 SCREENING CRITERIA FOR STD

6.1 Introduction

This concluding chapter develops criteria for screening proposals for the submarine disposal of mill tailings at new mines. A previously described example site selection procedure is also summarized, with comparisons of on-land and underwater disposal.

The Screening Criteria developed are intended for use by mine developers, for regulatory agencies that will eventually consider the proposals, and for the public at large.

A balance of screening criteria for environmental, logistic and socio-economic factors needs to be achieved. The actual balance will normally be site-specific and will depend on detailed knowledge of: the ore body, mineralogy of the tailing, processes generating the tailings, geographic setting, climate, oceanographic conditions, and many other mine and environmental factors. These factors can be divided into three basic groups (Table 6.1):

(1) Characteristics of the Receiving Area
(2) Characteristics of the Tailing Discharge
(3) Socio-economic Issues.

The order presented generally reflects relative ease in obtaining information. Some of the important characteristics of the receiving area can be simply determined from examination of existing hydrographic charts showing undersea topography, whereas socio-economic issues can be imprecise and exceptionally difficult to document.

It should be noted that in some of the documented cases, planning decisions about STD made, which in hindsight should not, or need not, have been made.

For example, the STD system initially adopted at the Black Angel Mine (Ch. 3) was unable to prevent contamination of the marine ecosystem. We now see that ther had been insufficient data gathering prior to decision making for design and placement of an STD system at that site.

In contrast, the decision at Cayeli Bakir to extend the discharge depth to 350 meters at about 3.5 km offshore will substantially increase costs and may increase operational difficulties and risks. However, the placement will allow discharge to a reducing environment, thus obviating the need for an onland acid waste treatment plant.

In reviewing the cases, we note that there is now substantial data on the experience of STD around the world. However, much of the data comes from systems constructed and environmentally assessed prior to recent technological and conceptual developments in tailings management and environmental impact assessment. Accordingly, although the case histories are informative, their features should not be transplanted without thorough assessment as to their relevance at new sites, using new materials and processes. It is important with new proposals for STD that the latest information and working concepts be considered. This applies not only

Table 6.1 Factors to be Considered in Developing Screening Criteria for Submarine Tailings Disposal.

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1. Characteristics of the Receiving Area

1.1 <u>Bathymetry</u>

Physical constraints on disposal

1.2 <u>Physical oceanography</u>

Influence on sediment and plume transport, dispersal and sedimentation
Near- and far-field behaviours
Prospects of upwelling and resuspensions
Water exchange rates, dilution effects
Slump and resuspension potential
Climate

1.3 <u>Outfall design and operation</u>

Design to prevent air entrainment, temperature and salinity differential effects
Security of emplacement
Performance criteria, case studies
Economics

1.4 <u>Chemical/Biological Oceanography</u>

Redox conditions in water and sediment
Diagenetic processes
Biological activity and resource species
Anticipated biological impacts

2. Characteristics of the waste discharge

2.1 <u>Solid Phase</u>

Mineralogies
Particle densities and size distributions
Sedimentation characteristics
Chemical stabilities and potential toxicities of dissolved constituents
Discharge rates

Table 6.1 Factors to be Considered in Developing Screening Criteria for Submarine Tailings Disposal contd.

2.2 Liquid phase

Residual milling chemicals - nature and potential toxicities
Dissolved heavy metals
Discharge rates

2.3 Slurry characteristics

Discharge rates and aggregation characteristics
Density current behaviour
Temperature and salinity differentials

3. Socio-economic Issues

Resource inventories
Economic and social impacts

to tailings management technology, but also to (1) knowledge of metals release as a function of milling processes and tailings characteristics (See Ch. 1.2 Acid Generation in Tailings and Ch. 3, Black Angel), and (2) procedures for environmental impact assessment.

In the context of metals release to the environment, and their subsequent low level concentrations in seawater, sediments and biological tissues, it should be noted that procedures for Quality Assurance/Quality Control (QA/QC) are essential. They encompass round-robin tests between co-operating laboratories, including those of regulatory agencies. QA/QC also involves the use of standardised and spiked samples provided by co-operating laboratories or by the mine's own environmental laboratory or its environmental consultants.

Morrissey (1993) provides an excellent summary of recent developments in EIA procedures. Essentially, a pilot survey of the environmental situation should be followed by strong scientific method. This means developing hypotheses concerning predictable changes, and sampling to meet contemporary standards of significance testing and power analysis. In addition, tailings deposition assessment lends itself to application of the Sediment Triad approach (Chapman, 1990): determine contamination levels by chemical analysis, determine toxicity levels by bioassays, and determine biological population effects by appropriate in situ parameters such as species health or biodiversity measures.

6.2 Onland and Underwater Comparisons

Caldwell and Welsh (1982) provided an overview and comparative assessment of tailing disposal methods, and included several lists and Tables which can function as check-lists of procedures.

There is, for example, a 7-step-procedure for tailings impoundment site selection, with an illustrative flow chart, followed by discussion of various onland impoundment options, the engineering involved, operational problems, and reclamation (Table 6.2).

The comparison of tailing disposal options includes a semi-objective appraisal system developed by the authors. This is based on assigning numerical values to impact levels (Table 6.3), and to operational and cost demands (Table 6.4).

They conclude with a reminder that the generalised comparative approach described is simple, and site-specific appraisals will need more sophisticated methods.

6.3 Screening Criteria

Criterion 1. Location

The mine-site must be sufficiently close to the coast, with an accessible route, that it is cost-effective to build, operate, maintain and protect the on-land transport system, whether pipeline or flumes, whether overland or through tunnels.

In general terms, tailing pipelines have been constructed and operated over 100 km distances. Hence a mine site within 100 kms of the coast potentially can use STD. However, with increasing distance and ruggedness, operational and security problems increase, such that site-

Table 6.2. Stepwise Procedure for Tailings Impoundment Site Selection (Modified from Caldwell and Welsh, 1982).

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1. **Regional screening.** Examine on topographic maps an area within a 10 km to 50 km radius of the site. Areas obviously unsuitable for tailings impoundments are eliminated. Some factors that may eliminate an area are: (a) topography too steep; (b) access too difficult; (c) sensitive ecological areas; (d) important land use zones; (e) too large a catchment area; (f) groundwater discharge area; and (g) unsuitable geology or mineralization.

2. **Site identification.** Identify all possible impoundment sites. List capacity, embankment height, distance from mine and other salient characteristics that might affect tailings disposal.

3. **Fatal flaw analysis.** Eliminate sites flawed by characteristics sufficiently unfavorable or severe that they preclude use of the site. Some such factors are: (a) unacceptable visual impact; (b) land use or ecological factors (such as critical fish or wildlife habitat); (c) archaeologically important sites; (d) too exposed to winds, flood plain, or active faults; (e) too small; and (f) too costly to develop.

4. **Investigate sites.** Visit the sites and gather as much data as possible about such factors as visibility, land use, meteorology, geology, soils, vegetation and groundwater. Formulate for each a conceptual design of an impoundment and hence estimate costs of construction operation and reclamation. Tabulate operational constraints or difficulties.

5. **Qualitative evaluation and ranking.** For defined factors, rate each site subjectively as very good, good, moderate, poor or very poor. Robertson and Moss (1981) list many factors; some may only be appropriate in particular cases.

6. **Semi-quantitative evaluation and ranking.** To each of the subjective ratings, assign and number - one for very good through 5 for very poor. Average ratings in similar categories such as operational, cost or environmental impact. Assign suitable weightings to each category; then add and determine a final numerical rating. The ranking of sites is according to these ratings.

7. **Detailed investigation.** The highest ranking sites are further investigated. This may involve field investigations, drilling, further design, costing and environmental studies and impact analysis. A minimum of two and preferably three sites should be studied in detail.

Table 6.3. Generalised Comparison Matrix of Environmental Impacts for Underwater and Onland Tailings Disposal Options (Modified from Caldwell and Welsh, 1982).

Environmental Factors	Deep Water Disposal	Flat Terrain	Rugged Terrain, High Rainfall, Seismic Area	In-pit Disposal	Dry Disposal in Rolling Country, Moderate Rainfall
Visibility	Very low	Very high	Moderate	Low	Moderate
Land use/ecology					
Area of disturbance	Very high	High	Moderate	Low	High
Long-term effect on:					
- vegetation	Very low	Moderate	Moderate	Very low	Moderate
- wildlife	Moderate	Moderate	Moderate	Very low	Moderate
- human use	Very low	Moderate	Moderate	Very low	Moderate
Airborne release potential	Very low	High	High	Moderate	Very high
Seepage release potential	Very high	High	Low	Low	Very low
Surface release pollution characteristics					
- Concentrated flow	Very low	Low	High	Very low	Low
- Erosion	Very low	Moderate	High	Very low	High
- Foundation failure	Very low	Low	Moderate	Very low	Low
- Liquefaction	Very low	Low	Very high	Very low	Very low
Semi-qualitative evaluation					
- Total	21	38	41	17	31
- Average	1.9	3.5	3.7	1.6	2.8

Table 6.4. Generalised Comparison Matrix of Cost and Operations for Underwater and Onland Tailings Disposal Options (Modified from Caldwell and Welsh, 1982).

Environmental Factors	Deep Water Disposal	Flat Terrain	Rugged Terrain, High Rainfall, Seismic Area	In-pit Disposal	Dry Disposal in Rolling Country, Moderate Rainfall
Operational storage capacity	Very good	Moderate	Good	Poor	Moderate
Need for construction materials	Very low	Moderate	Very high	Very low	Low
Expansion capacity	Very good	Good	Moderate	Poor	Good
Surface drainage control requirements	Very low	Moderate	Very high	Moderate	Moderate
Operating difficulties	Low	Moderate	High	Very high	Moderate
Semi-qualitative evaluation					
- Total	6	14	19	17	13
- Average	1.2	2.8	3.8	3.4	2.6

specific topography, scouring potential, sabotage risk, etc. will determine what distance is cost-effective at any site compared to the alternatives for tailings disposal.

Criterion 2. Bathymetry and Physical Oceanography

Part 1. (Option A). Silled fjord or other embayment enclosing a deep basin; with side slope allowing formation of a tailings density current; of sufficient volume for tailings containment below the euphotic zone; and sufficient soft-bottom depositional area.

The euphotic zone in simple terms is the near-surface water to which sunlight penetrates and marine plants grow. The zone ranges in depth from about 10-100 meters depending on water turbidity.

(Option B). Nearshore slope, with or without an incised canyon, to depths below the euphotic zone, with gradient sufficient to form and maintain a tailings density current, and subsequent flow to a suitable deposition site.

Note that a minimum slope cannot be usefully defined. Tailings density current formation and flow depend on many factors including ore composition, mill grind, particle size distribution, particle specific gravity, sea-water mix capability, exit jet velocities, seawater dynamics, and distance of slope. Near-field tailings dispersal models have been developed (See Vol. 1, Appendix A on the Quartz Hill Development), but they need site-specific modification.

Part 2. Quiescent subsurface water without seasonal overturning or upwelling in order to keep tailings from resuspending into the euphotic zone.

Criterion 3. Tailings Outfall

A site must be available for construction of an outfall designed to maximise density current flow to the chosen deposition area. The site must allow, if appropriate, construction of a de-aeration chamber, a sea-water intake line from an appropriate depth, and a mixing-chamber. These may be needed within the system so as to achieve a slurry density minimising the possibility of a buoyant plume of the fine fraction separating from the tailings density current.

Criterion 4. Potential for Bioactivation of Contaminants

Chemical composition of the tailings discharge and the receiving seawater must minimize the potential for contaminant leaching with subsequent biological impact. In general terms low oxygen level within the receiving water is desirable, but is not an essential criterion. Leaching and bioassay tests (short and long-term) of representative tailing samples are essential.

Criterion 5. Suspension and Upwelling

Part 1. The tailings density current formed must minimize suspension of fine tailings particles, and must flow coherently to the final deposition site.

Part 2. After deposition, physical oceanographic forces (upwelling or lateral currents) must be so slight that a minimal amount of tailings fines is resuspended, and upwelled into the euphotic zone.

Criterion 6. Multiple Resource Use

Part 1. Other resource-use potential, particularly biological resources such as fisheries, must not be permanently destroyed.

Part 2. Where particular resources (whether currently in use or not) will be impacted, there must be potential for recovery by identical or alternative resources.

Criterion 7. Socio-economic Factors

Where particular resources are lost, the socio-economic importance of these must be appraised for appropriate compensatory measures. Such losses may be permanent or temporary, and the time-scale needs appraisal for the compensatory measures.

6.4 Step-wise Implementation of Screening Criteria

The most important Criteria are nos. 1-4: Location, Bathymetry, Outfall Placement, and Leaching Potential. Preliminary information about these criteria can determine whether the others need to be considered at all.

Following favorable evaluation that location, bathymetry, outfall placement and leaching potential are suitable in principle for STD, then the other Criteria can be considered. This has the practical merit that if STD is inappropriate it can be eliminated by relatively inexpensive preliminary surveys. Thus the far more expensive detailed environmental surveys need not be started until STD is established as conceptually sound.

A stepwise procedure for appraising the Criteria in a rational and cost-effective sequence is presented (Table 6.5), and illustrated in Figure 6.1. It should be noted that after Action 3, the more extensive data gathering for Actions 4-7 should proceed concurrently; even though the Actions can be appraised consecutively in the order shown.

Table 6.5 Stepwise Procedure for Progressive Consideration of STD.

A decision to evaluate STD may be either on the concept in principle, or for STD at a specific site. If a rejection is for a specific site or design, it may be possible to redesign a proposal to meet objections raised.

<u>Action 1</u>. Determine on-land topography and alternative routes for tailings transport to coastline by pipeline, flumes and/or tunnels (Criterion 1), and availability of sites for outfall placement (Criterion 3).

Apply Criteria 1 and 3. If preliminary appraisals of topography, design of on-land transport systems, and maintenance appear cost-effective, proceed to Action 2. If not reject the STD concepts developed.

<u>Action 2</u>. Determine Bathymetry and Physical Oceanography of Potential Receiving Areas for application of Criterion 2.

1. Fiord present?
2. If open coast, is slope to appropriate depth available?
3. Is seawater stratification present and persistant?
4. Soft-bottom depositional area present?

Apply Criterion 2. If an apparently suitable deposition site is available start Action 3, otherwise reject the specific STD concept(s) proposed.

<u>Action 3</u>. Undertake Reconnaissance Level Feasibility Study, for first consideration of all other Criteria.

1. Chemical characterisation of ore, and trace metal leaching tests.
2. Current resource uses.
3. Important social considerations.
4. Preliminary community concerns.

Consider all Criteria. If there is no obvious rejection, eg permanent loss of important fisheries, unanimous community hostility, etc., of a specific STD proposal by application of any of the Screening Criteria, proceed to obtain information on Actions 4, 5, 6 and 7 concurrently.

Table 6.5 Stepwise Procedure for Progressive Consideration of STD contd.

<u>Action 4</u>. Determine Waste Discharge Characteristics

1. Ore body - size, chemical composition, acid leaching potential, intended mining rate, expected mine lifetime.
2. Mill - mill process, process chemicals, residual reagents.
3. Test milling - tailings characteristics (physical and chemical), bioassays and leaching tests (acute, long-term, lethal, sublethal).
4. Marginal ore stockpile plans.
5. Other waste discharges - marine, land or air.
6. Existing waste discharge controls.
7. Compatibility of expected waste discharge with controls.

Apply Criterion 5. If expected waste discharge characteristics are compatible with existing discharge controls, or acceptable modifications of the controls, proceed to consider results of Action 6.

<u>Action 5</u>. Determination of Other Resources and Uses - Actual and Potential

1. Fisheries - actual and potential.
2. Survey of the aquatic ecosystem - sea, estuaries and rivers.
3. Other resource uses - biological, mineral, energy, transport, recreation, etc.
4. Traditional rights, uses and values.
5. Compatability potential - co-existance with the mine, and/or subsequent recovery after mine closure (natural recolonisation and/or engineered reclamation).
6. Compensation potential.

Apply Criteria 6 and 7. If there is compatible use of other resources by co-existance, and/or subsequent recovery after the mine eventually closes, or if compensation for lost resources is negotiable, proceed to consider results of Action 5.

<u>Action 6</u>. Surveys to facilitate design of the STD

1. Receiving area topography - coastal and submarine.
2. On-land systems - tailings transport system to coast, outfall location and design.
3. Physical oceanography - currents, density structure, variability (tidal, seasonal and long-term).
4. Tailings nearfield dispersal - model predictions.

Table 6.5 Stepwise Procedure for Progressive Consideration of STD contd.

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5. Marine sedimentology - natural sediment origins and deposition patterns, pore water chemistry.
6. Tailings far-field dispersal - model predictions, impacts (physical chemical and benthic), area affected and rate of extension over mine lifetime.
7. Chemical and biological oceanography - water column.
8. Liquid fraction dispersal - model predictions, impacts (chemical and biological), area affected and rate of extension over mine lifetime.

Apply Criteria 3, 4 and 5. If acceptably small impacts (permanent or temporary), or acceptably small risk of such impacts, proceed to consider results of Action 7.

<u>Action 7</u>. Development of community input

1. Identify community groups and interests.
2. Develop and start procedures for regular public input.
3. Identify permitting procedures, and potential permit conditions.
4. Identify community concerns requiring further action, and take appropriate action.

Apply Criterion 7. If concerns expressed and their resolutions are generally acceptable to the community, project proceeds to formal permitting stage.

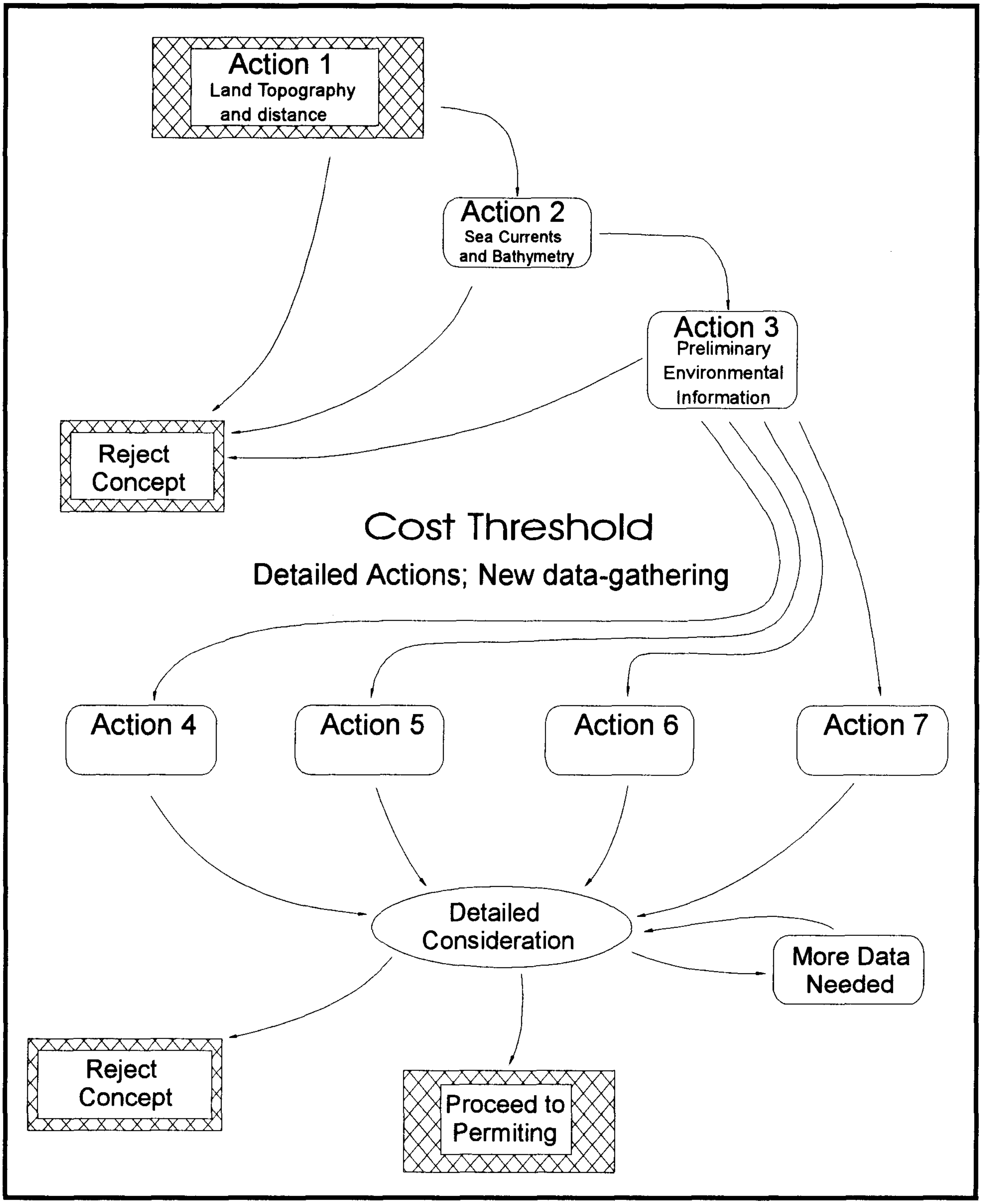


Figure 6.1 - Flow Diagram of Actions for Applying Screening Criteria to a Mine Development.

7.0 REFERENCES

Alino P.M. 1984. The effects of mine tailings on the structure of coral communities in Toledo, Cebu. Presented during 3rd Symposium on Our Environment, Singapore, 27-29th March 1984.

Alino P.M. 1983. The effects of mine tailings on the structure of coral communities in Toledo, Cebu. M.Sc. thesis, University of the Philippines, Diliman, QC 105 pp (Not seen).

Alldredge, A.L., and McGillivary P. 1991. The attachment probabilities of marine snow and their implications for particle coagulation in the ocean. *Deep-Sea Res*. 38(4A) 431-443.

Amy P.S., Caldwell, B.A., Soeldner, A.H., Morita R.Y. and Albright L.J. 1987. Microbial activity and ultrastructure of mineral-based marine snow from Howe Sound, British Columbia. *Can. J. Fish. Aquat. Sci.* 44:1135-1142.

Anon 1978. *Sedimentation in Recipients. Disposal of Particulate Mine Waste.* Royal Norwegian Council for Scientific and Technical Research. ISBN 82-595-1691-8 72 pp.

Anon 1992. Freeport's extension of gloom for the Amungme. tapol Bulletin No. 109.

Anon 1993. Interim policy for acid rock drainage at mine sites. B.C. Ministry of Energy, Mines and Petroleum Resources (Draft).

Applied Geology Associates Ltd. 1989. Bougainville Copper Mine, Panguna. Environmental Socio-Economic Public Health Review. Rept. to Ministry for Minerals and Energy, PNG.

Asmund, G., 1992. Pollution from the marine tailings disposal at the lead-zinc mine at Maarmorilik, West Greenland, Envir. Issues & Waste Management. In Singhal *et al.* (Editors) 1992 *Energy & Minerals Production*, Balkema Rotterdam. pp 587-594.

Asmund, G., and Hansen M.M. and Johansen, P. 1988. Environmental impact of marine tailings disposal at the lead-zinc mine at Maarmorilik, West Greenland. Proceeding of Conference on Control of Environmental Problems from Metal Mines. Roros, Norway, June, 1988.

Asmund, G., Christopherson, J.B. and Steenshoe, J., 1990. Rehabilitation and demolition after the closure of the zinc and lead mine *Black Angel* at Maarmorilik, Greenland. Proc. Polartech 90, Aug.1990.

Asmund, G., Bollingberg, H.J. and Bondam, J., 1975. Continued environmental studies in the Qaumarujuk and Agfardlikavsa fjords, Marmorilik, Umanak district, Central West Greenland, Geol. Surv. Greenland Rep. 80,53-61.

B.C. Research 1972. Marine survey and sampling off Marmorilik in West Greenland. Project Rept, Part I. Rept. for Cominco.

B.C. Research. 1980. Sampling at Marmorilik, October, 1979. Rept. for Greenex A/S.

B.C. Research. 1978. Inhibition of heavy metal dissolution from Black Angel Mine tailing, March 1978. Rept. for Greenex A/S.

B.C. Research. 1976. Sampling and analysis of fish from Qaumaruk Fjord, March 1976. July 1976. Rept. for Greenex A/S.

B.C. Research. 1983. Sampling at Marmorilik, September 1983. Rept. for Greenex A/S.

B.C. Research. 1982. Sampling at Marmorilik, September, 1980. Rept. for Greenex A/S.

B.C. Research. 1983. Sampling at Marmorilik, September, 1981. Rept. for Greenex A/S.

B.C. Research. 1977. Report on marine samples collected from Marmorilik in September 1976. May 1977. Rept. for Greenex A/S.

B.C. Research. 1976. Report on seawater samples collected from Marmorilik, West Greenland, in March 1976. May 1976. Rept to Greenex A/S.

B.C. Research. 1973. Chemical analyses for arsenic and mercury of samples collected during the marine survey off Marmorilik, West Greenland, August 1972. April 1973. Project Rept. Part II. Addendum. Rept. for Cominco.

B.C. Research. 1981. Sampling at Marmorilik, September, 1980. Rept. for Greenex A/S.

B.C. Research 1974. Trace metal concentrations in the marine environment off Marmorilik, West Greenland, July 1973. January 1974. Project Rept. for Cominco.

B.C. Research 1973. Chemical analyses of samples collected during the marine survey off Marmorilik, West Greenland, August 1972. March 1973. Project Rept, Part II. Rept. for Cominco.

B.C. Research. 1974. Arsenic concentration in marine samples from Marmorilik, West Greenland, July 1973. March 1974. Project Rept. for Cominco.

Bird, G.J., and Holdich, D.M. 1989. Recolonisation of artificial sediments in the deep Bay of

Biscay by tanaidaceans (Crustaces: Peracarida), with a description of a new species of Pseudotanais. *J. Mar. Biol. Assoc. U.K.* 69(2) 307-327.

Bollingberg, H.J. and Johansen, P., 1979. Lead in spotted wolffish, *Anarhichas minor*, near a zinc-lead mine in Greenland. *J.Fish.Res.Bd. of Canada*, 36,1023-1028.

Bondam, J. and Asmond, G. 1973. Environmental studies in the Qaumarujuk and Agfardlikavsa fjords, Umanak district, Central West Greenland, *Gronlands Geol. Unders*. 65, 29-33.

Bourcier, M 1970. Ecoulement des boues rouges dans le canyon de la Cassidaigne (decembre 1968) *Tethys*, 1(3) 1969, 779-782.

Bourcier, M. and Zibrowius, H. 1973. Les "Boues Rouges" deversees dans le Canyon de la Cassidaigne (region de Marseille) Observations en soucoupe plongeante SP 350 (juin 1971) et resultats de dragages. *Tethys* 4(4) 811-842.

Bridges G. 1978. A presentation of objections and recommendations to the Pollution Control Board's Hearing on the Jordan River Mines application for a pollution discharge permit. Submission to a simulated public inquiry, University of Victoria.

Caldwell, J.A. and J.D. Welsh 1982. Tailings disposal in rugged, high precipitation environments: an overview and comparative assessment. Ch. 1, pp 5-62 In Ellis D.V. (Editor) 1982 *Marine Tailings Disposal.* Ann Arbor Science, USA. 368 pp.

Canfield D.E. and Des Marais D.J. 1991. Aerobic sulfate reduction in microbial mats. Science 251, 1471-1473.

Chapman, P.M. 1990. The sediment quality triad approach to determining pollution - induced degradation. *The Science of the Total Environment*, 97/98 pp 815-825.

Chen K.Y. and Morris J.C. 1972a. Kinetics of oxidation of aqueous sulfide by O_2. *Environ. Sci. Technol.* 6, 529-537.

Chen K.Y. and Morris J.C. 1972b. Oxidation of sulfide by O_2: catalysis and inhibition. *J. Sanit. Eng. Div. Proc. Amer. Soc. Civ. Eng.* 98, 215-227.

Cline J.D. 1969. Oxygentation of hydrogen sulfide in seawater at constant salinity, temperature, and pH. *Environ. Sci. Technol.* 3, 838-843.

Cypionka H., Widdel F. and Pfennig N. 1985. Survival of sulfate-reducing bacteria after oxygen stress, and growth in sulfate-free oxygen-sulfide gradients. *FEMS Microbiology Ecology* 31, 39-45.

Diaz D.B., Reyes B.J., Huaman J.R.T. and Ramos F.C. 1991. The irrational water management by the mining industry in the south of Peru. Case document to the 2nd International Water Tribunal.

Dilling W. and Cypionka H. 1990. Aerobic respiration in the sulfate-reducing bacteria. *FEMS Micrbiol. Lett.* 71, 123-128.

Dira D.C. and Canete A.V. 1980. ACMDC'S Tailings Disposal Today. 6th Symp. Min. Res. Devt and 27th Ann Mine Safety Conf.

Guevara V.V. 1981. Questionnaire Responses. XIV International Mineral Processing Congress, Oct 17-23, 1981, Toronto.

Eagle, A.M. and R.J.Higgins. 1988. An example of modern environmental impact assessment. Ok Tedi mining Ltd.

Elder H 1973. Letter to Director, Pollution Control Branch, Victoria, B.C.

Ellis D.V. 1989. Bougainville Copper Mine (Papua New Guinea). Ch 9, pp 225-241 in Ellis, D.V. 1989 *Environments at Risk. Case Histories of Environmental Impact*. Springer-Verlag, NY 329 pp.

Ellis D.V. 1987. A decade of environmental impact assessment at marine and coastal mines. *Marine Mining* 6:385-417.

Ellis D.V. 1975b. Rehabilitation of the marine receiving area at Jordan River Mine: Report 1975 and Assessment Proposal 1976. Rept to Pollution Control Branch 38 pp.

Ellis D.V. 1984. The Aquatic Resource Programme at Bougainville Copper Mine. Rept. to Bougainville Copper Ltd. 105 pp.

Ellis D.V. 1988. Case histories of coastal and marine mines Ch 4 pp 74-100 in Salomons W. and Foerstner U. (Editors) 1988 *Chemistry and Biology of Solid Waste* Springer, Berlin 305pp.

Ellis D.V. 1989. *Environments at Risk: Case Histories of Impact Assessment* Springer-Verlag, Berlin. 329 pp.

Ellis D.V., Pelletier C.A., and Jordan A.J. 1981. Marcopper marine tailings discharge assessment. Rescan. Rep. Marcopper Mining Corp. 83pp.

Ellis D.V. 1989. Environmental audits - Marcopper Mining Corp. (The Philippines.) Ch 9:215-241 in Ellis, D.V. 1989 *Environments at Risk* Springer, Berlin 329pp.

Ellis D.V. 1975a. Pollution controls on mine discharges to the sea. *Proc. Int. Conf. Heavy*

Metals in the Environment, Toronto, pp 677-686.

Ellis D.V. 1980. Environmental consequences of breaks and interrupted construction at marine outfalls in British Columbia pp 123-126 in *Coastal Discharges Proc. Institution Civil Engineers*, London.

Ellis, D.V., and Heim, C. 1985. Submersible surveys of benthos near a turbidity cloud. *Mar. Poll. Bull.* 16(5) 197-203.

Ellis D.V. and Popham J.D. 1983. Accidental formation and subsequent disappearence of a contaminated beach: A case history of environmental management pp 719-776 in Maclachlan, A., and Erasmus, T. (Editors) 1983 *Sandy Beaches as Ecosystems* Junk, The Hague 757pp.

Ellis, D.V., and Hoover P.M. 1990. Benthos in tailings beds from an abandoned coastal mine. *Mar. Pollut. Bull.*, V.21, No. 10. pp 477-480.

Ellis, D.V. and Taylor, L.A. 1988. Biological engineering of marine tailings beds. pp 185-207. In Salomons W. and Foerstner U. (Editors) 1988 *Environmental Management of Solid Waste*. Springer, Berlin Heidelberg New York Tokyo.

Ellis, D.V., and Hoover P.M. 1991. Benthos recolonizing mine tailings in British Columbia fjords. *Marine Mining* (9): 441-457.

Ellis D.V. 1977. Effectiveness of Existing Pollution controls as Shown by Four Case-Histories; and recommendations for future control. Submission to Public Inquiry into Pollution Control Objectives, Victoria, BC.

Gross, T.F., and Dade, W.B. 1991. Suspended sediment storm modeling. *Mar. Geol*, 99(3-4) 343-360.

Hammer, R.M.,Balcon, B.J., Cruickshank, M.J. and Morgan, C.L. 1993. Synthesis and analysis of existing information regarding environmental effects of marine mining. Final Report to Minerals Management Service, U.S.Dept. Interior. 392 pp.

Hardy J.A. and Hamilton W.A. 1981. The oxygen tolerance of sulfate-reducing bacteria isolated from North Sea waters *Cur. Microbiol.* 6, 259-262.

Hastings D. and Emerson S. 1988. Sulphate reduction in the presence of low oxygen levels in the water column of the Cariaco Trench. *Limnol. Oceanogr.* 33, 391-396.

Hay, A.E., Burling, R.W., and Murray, J.W., 1982. Remote acoustic detection of a turbidity current surge. *Science*. 217, 833-835.

Hay, A.E., Murray, J.W. and Burling R.W. 1983a. Submarine channels in Rupert Inlet, British Columbia: I. Morphology. *Sedimentary Geology* 36 289-315.

Hay, A.E., Murray, J.W. and Burling, R.W. 1983b. Submarine channels in Rupert Inlet, British Columbia: II Sediments and sedimentary structures. *Sedimentary Geology* 36 317-339.

Hesse, C.A. and Reim, K.M. 1993. Regulatory aspects of submarine tailings disposal - The Quartz Hill Case History. Rept to U.S. Bureau of Mines, Juneau, Alaska. 85 pp.

Hollister, C.D., and Nowell, A.R.M. 1991. HEBBLE epilogue. *Mar. Geol.* 99(3-4) 445-460.

Howarth R.W. and Giblin A. 1983. Sulfate reduction in the salt marshes at Sapelo Island, Georgia. *Limnol. Oceanogr.* 28, 70-82.

Hughes, P.J. 1989. The effects of mining on the environment of high islands: A case study of gold mining on Misima Island, Papua New Guinea. In *Environmental Case Studies*, South Pacific Study 5. South Pacific Commission. 6 pp.

Hughes P.J. 1989. The effects of mining on the environment of high islands: a case study of gold mining on Misima Island, Papua New Guinea. South Pacific Study 5, South Pacific Regional Environment Program (SPREP).

Hughes P and M.Sullivan 1991. The environmental effects of mining and petroleum production in Papua New Guinea. Authors' manuscript.

Hughes P and M. Sullivan 1989. Environmental impact assessment in Papua New Guinea: lessons for the wider Pacific region. *Pacific Viewpoint* 30(1), 34-55.

International Water Tribunal 1992. Judgement Southern Peru Copper corporation. 3 pp.

International Water Tribunal 1991. Newsletter 4. 29 pp.

Island Copper Mine. 1992. Annual Environmental Assessment Report. BHP-UTAH Mines Ltd.

Johansen, P., Hansen, M.M., Asmund, G. and Nielsen, P.B. 1991. Marine organisms as indicators of heavy metal pollution - Experience from 16 years of monitoring at a lead zinc mine in Greenland. *Chem. and Ecology* 5, 35-55.

Jorgensen B.B. 1982. Ecology of the bacteria of the sulphur cycle with special reference to anoxic-oxic interface environments. *Phil. Trans. R. Soc. Lond.* B298, 543-561.

Jorgensen B.B. 1977. The sulfur cycle of a coastal marine sediment (Limfjorden, Denmark). *Limnol. Oceanogr.* 22, 814-832.

Kabutaulaka T.T. 1993. The Nation Next door: the Bougainville Crisis and Solomon Islands. Manuscript, University of the South Pacific.

Kilby, C.A. 1991. Nearshore surficial geology, heavy minerals and geochemistry, Northern Juan de Fuca Strait. M.Sc. thesis, University of Victoria. 302 pp.

Krank, K. 1984. Grain-size characteristics of turbidites. *Geol. Soc. London* Sp.Pub.15, 83-92.

Kuit, W.J. 1979. The Control of soluble metals associated with marine tailings disposal at Marmorilik, Greenland. *Cominco Tech. Res.* Jan.

Laborel, J., Peres, J.M. Picard, J. and Vacelet, J. 1961. Etude directe des fonds des parages de Marseille de 30 a 300 m avec la soucoupe plongeante Cousteau. *Bull. Inst. Oceanogr. Monaco*, 58(1206), 1-16.

Linke, P. 1992. Metabolic adaptations of deep-sea benthic foraminifera to seasonally varying food input. *Mar. Ecol. Prog. Ser.* 81(1) 51-63.

Lister D, Poling G.W., Horne, I.A. and Li, M.G. 1993. Prediction and reality: static analyses versus actual rock weathering in waste dumps at Island Copper Mine, Port Hardy, B.C. Proc. 1993 B.C. Mine Reclamation Symposium.

Littlepage, J.L. and Ellis, D.V. 1972. An oceanographic survey of Qaumarujuk and Agfardlikavsa Fjords, Marmorilik, Greenland. (Rept. to Cominco).

Littlepage J.L. 1973. Behaviour of Tailings-Derived Sediments on Offshore Areas near Jordan river. Report to Davis and Company, Vancouver.

Martin W.R., and Bender, M.L. 1988. The variability of benthic fluxes and sedimentary remineralization rates in response to seasonally variable organic carbon rain rates in the deep sea: A modeling study. *Am. J. Sci.* 288(6) 561-574.

McAllister D.E. 1987. Mine pollution at Marinduque Island in the Philippines *Sea Wind* 1(3), pp 26-27.

McCave, I.N. and Jones, K.P.N. 1988. Deposition of ungraded muds from non-turbulent turbidity currents. *Nature* 333, 250-252.

McGreer, E.R. 1980. Availability of metals from inorganic particulates (mine tailings) for uptake by marine invertebrates. Rept. EVS Consultants.

Meidinger D 1978. Assessment of Copper Contamination from Previous Discharges from Jordan River Mine. Submission to a simulated public inquiry, University of Victoria.

Mikkelborg, E. 1974. Looking over the Black Angel shoulder. *Canadian Mining Journal*, pp 24-36. August.

Moller, J.S. 1984. Hydrodynamics of an arctic fjord. Inst. Hydrodynamics and Hydraulic engineering, Tech. Univ. Denmark, Ser. Paper 34. 97 pp.

Morrisey, D.J. 1993. Environmental impact assessment - a review of its aims and recent developments. *Mar. Poll. Bull.* Vol 26, No 10, pp 540-545.

Natural Systems Research Pty. Ltd. 1982. Misima project Enviromental Investigations, Milne Bay, PNG, Phase I Report. Rept. to Placer PNG) Pty Ltd.

Natural Systems Research Pty. Ltd. 1987. Misima Project Environmental Plan. Rept.to Placer (PNG) Pty. Ltd. 3 Volumes. (Not seen).

Natural Systems Research Pty. Ltd. 1986. Misima Project Draft Environmental Plan. Rept.to Placer (PNG) Pty. Ltd. 3 Volumes.

Nedwell D.B. 1982. The cycling of sulphur in marine and freshwater sediments. In Nedwell D.B. and Brown C.M. (Editors) 1982 *Sediment Microbiology* 73-106.

Nielsen, T.K. and Ottsen Hansen, N.E., 1980. Mixing and exchange processes in a small Greenland sill-fjord. pp 219-225. In Freeland H.J., Farmer, D.M. and Levings C.D. (Editors) 1980 *Fjord Oceanography*. Plenum Press.

Northcote T.G. and Hall K.J. 1983. Limnological contrasts and anomalies in two adjacent saline lakes. *Hydrobiologia* 105, 179-194.

Oliver D. 1981. Aspects of modernization in Bougainville, Papua New Guinea. Center Asian Pacific studies, Univ. Hawaii Manoa, Pacific Islands Studies Working Paper Series.

Pedersen T.F. 1985. Early diagenesis of copper and molybdenum in mine tailings and natural sediments in Rupert and Holberg inlets, British Columbia. *Can. J. Earth Sci.* 22, 1474-1484.

Pedersen T.F. and Losher A.J. 1988. Diagenetic processes in aquatic mine tailings deposits in British Columbia. pp 238-258 In Salomons W. and Forstner U. (Editors) 1988 *Chemistry and Biology of Solid Waste. Dredged Material and Mine Tailings.* Springer-Verlag Berlin.

Pentreath, R.J., Hargrave, B.T., Roe H.S.J., and Sibuet M. 1988. Deep-sea biology, biological processes and radiobiology. Vol 6 In Nuclear Energy Agency *Feasibility of Disposal of High-Level Radioactive Waste into the Seabed.* OECD Publications, France. 219 pp.

Pfennig N. and Widdel F. 1982. The bacteria of the sulphur cycle. *Phil. Trans. R. Soc. Lord.* B298, 427-435.

Poling G and Ellis D. (Editors) 1993. Case studies of Submarine Tailings Disposal: Volume I - North American Examples. Rept. to U.S. Bureau of Mines.

Postgate J.R. 1984. *The sulphate-reducing bacteria.* Cambridge University Press.

Powell, J. 1984. Marine Environmental Impact Assessment of Tailings Disposal at Bougainville Island. Rept. to Bougainville Copper Ltd. 38 pp.

Rawson Academy of Aquatic Science 1992. A Critical Review of MEND studies conducted to 1991 on subaqueous disposal of tailings. Rept. to Canada Centre for Mineral and Energy Technology.

Rescan Environmental Services Ltd. 1989. Environmental impact statement, San Antonio Copper Project. Rept. to Marcopper Mining Corporation.

Rescan Consultants Inc. 1993. Regulation of submarine tailings disposal. Rept. to US Bureau Mines.

Rescan Environmental Services Ltd. 1990. A preliminary assessment of subaqueous tailings disposal in Benson Lake, British Columbia. Rept. to B.C. Min. of Energy, Mines and Petroleum Resources and others.

Rescan Environmental Services Ltd. 1992. Chemical diagenesis of submerged mine tailings in Benson Lake and natural sediments in Keogh Lake, Vancouver Island, B.C. Rept. to Placer Dome Inc.

Rescan Environmental Services Ltd. 1989. Subaqueous disposal of reactive mine wastes. Rept.for B.C. Acid Mine Drainage Task Force.

Rescan Environmental Services Ltd 1990. Misima Project. Compliance validation of submarine tailings discharge. Rept. to Dept. Minerals and Energy, Papua New Guinea.

Rescan Consultants Inc. 1992a. Cayeli Bakir Project. Tailings disposal feasibility and basic engineering. Rept. to Cayeli Bakir Isletmeleri, A.S.

Rescan Consultants Inc. 1992c. Cayeli Bakir Project. Response to environmental issues identified in International Finance Corporation external review. Rept. to Cayeli Bakir Isletmeleri, A.S.

Rescan Consultants Inc. 1992. Offshore tailings disposal. Environmental Impact Assessment. Rept to Southern Peru Copper Corporation.

Rescan Consultants Inc. 1992b. Cayeli Bakir Project. Submarine tailings pipeline: potential sources of damage, repair methods and advisability of providing a backup pipeline. Rept. to Cayeli Bakir Isletmeleri, A.S.

Robertson, A.M. and Moss A.S.E. 1981. Site selection and optimization for mill sites and tailings impoundments. Proc. Asian Mining Conference.

RTZ 1990. Bougainville Copper Ltd - AGM Chairman's Supplementary Comments. Press Release by RTZ.

Wasi J.W. 1993. An Internal Conflict, a Regional Problem? The case of the Bougainville Crisis. Course report, University of the South Pacific, 28 pp.

Salazar R.C and Gonzales R.I. 1973. Design, construction and operation of the tailings pipelines and underwater tailings disposal system of Atlas Consolidated Mining and Development Corporation in the Philippines. Ch. 20, pp 477-511. In Aplin, C.L, and Argall, G.O. (Editors) 1973 *Tailing Disposal Today.* Proc. 1st Int. Tailing symp, Tucson, Arizona, Oct 31-Nov 3, 1972. 861 pp.

Salazar R.C. and Dira D.C. 1977. The tailings disposal system of Atlas consolidated Mining and Development Corporation. 5th Symp. Min. Res. Devt and 24th Ann Mine Safety Conference, Philippines.

Sibuet, M. 1992. Deep-sea benthic ecosystems: dynamic aspects. Ch. 16 pp 319-333. In Hsu, K.J. and Thiede J. (Editors) 1992 *Use and Misuse of the Seafloor* John Wiley & Sons Ltd.

Sibuet, M., and Juniper, K. 1986. Benthic ecology of the abyssal plain: an overview. Rept. to Dept. Environ. Profond, IFREMER, Brest. 59 pp.

Sibuet, M. 1987. Structure des peuplements benthiques en relation avec les conditions trophiques en milieu abyssal dans l'ocean Atlantique. Cas particulier des echinodermes. 2 Vols. These de Doctorat d'etat, Univ. Pierre et Marie Curie, Paris VI. 693 pp.

Snelgrove, P.V.R., Grassle, J.F., and Petrecca, R.F. 1992. The role of food patches in maintaining high deep-sea diversity; Field experiments with hydrodynamically unbiased colonization trays. *Limnol. Oceanogr.* 37(7) 1543-1550.

Sorensen J., Christensen D. and Jorgensen B.B. 1981. Volatile fatty acids and hydrogen as substrates for sulfate-reducing bacteria and anaerobic marine sediment. *Appl. Environ. Microbiol.* 42, 5-11.

Sorokin Y.I. 1972. The bacterial population and the processes of hydrogen sulphide oxidation in the Black Sea. *J. Cons. Int. Explor. Mer* 34, 423-454.

SPCC 1992. Preliminary Environmental Assessment Offshore Tailings disposal. Southern Peru Copper corporation.

Thiel, H 1991. From MESEDA to DISCOL: a new approach to deep-sea mining risk assessments. *Marine Mining* 10(4), 369-386.

Thiel, H., Foell, F. and Schriever, G. 1991. Potential environmental effects of deep seabed mining. Nr.26 Institute fur Hydrobiologie und Fischereiwissenschaft, Hamburg. 243 pp.

Thiel, H. 1992. Deep-sea environmental disturbance and recovery potential. *Int. Revue ges. Hydrobiol.* 77(2) 331-339.

Tilot, V. 1992. La structure des assemblages megabenthiques d'une province a nodules polymetalliques de l'ocean Pacifique tropical Est. These de Doctorat de l'Univ. de Bretagne Occidentale. 380 pp.

Titus J 1978. Jordan River. General Social Information. Submission to a simulated public inquiry, University of Victoria.

Trono G.C. 1988. Resurvey Report. Rept to Marcopper mine. 3 pp.

Vacelet, J. 1968. Eponges de la Roche du Large et de l'Etage Bathyal de Mediterranee (recoltes de la soucoupe plogeante Cousteau et draggages). *Mem. Mus. Hist. Nat.*, Paris, (n.S., A, Zool.) 59(2), 145-219.

Velasquez M.A.. 1987. The destruction of Calancan Bay. APEN. 4(4), p3.

Venables, W.N. 1973. Letter of Transmittal, Effluent Discharge Permit No.PE-427P. B.C. Dept. Lands, Forests and Water Resources.

Wadey, R.H. 1972. Greenex Operations: Tailings. Draft Agreement.

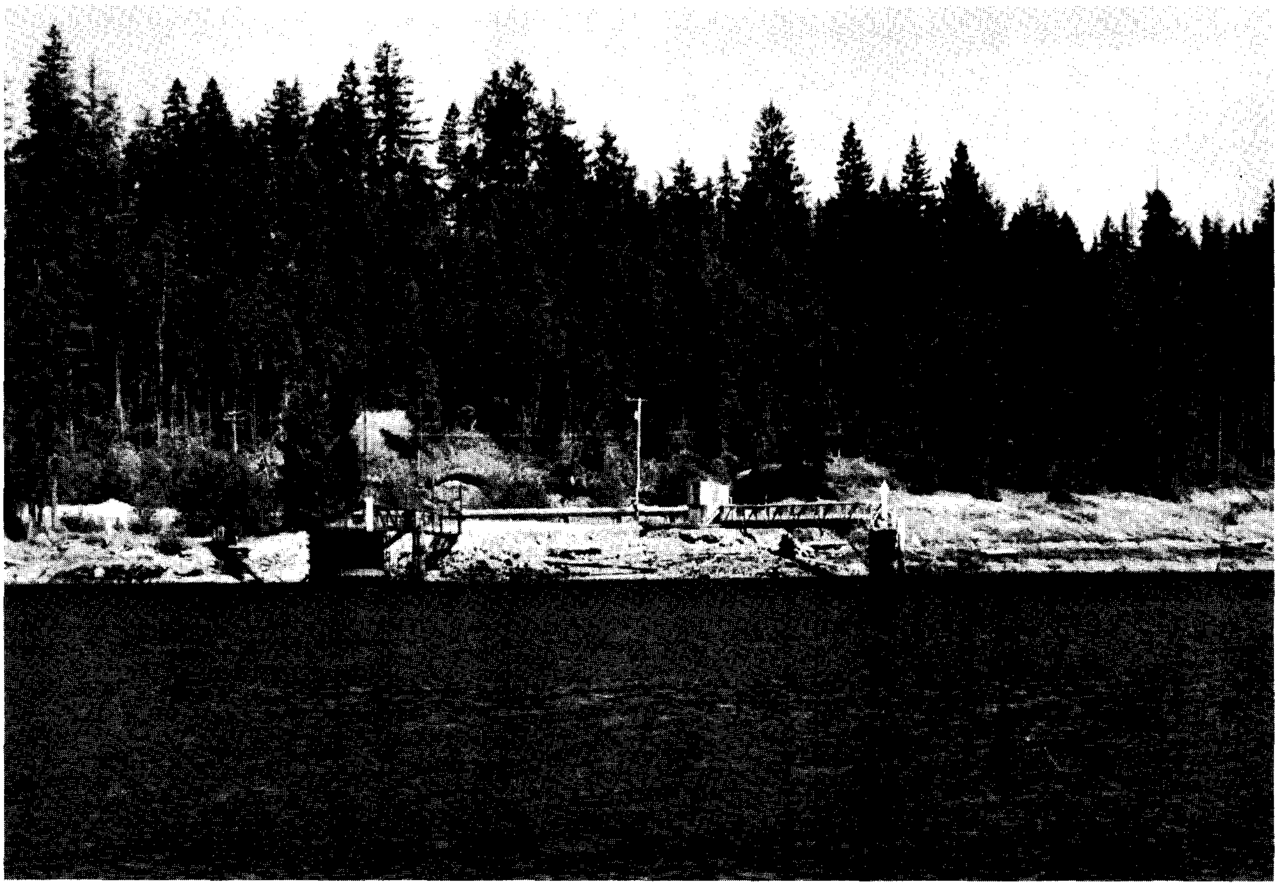
Wetzel R.G. 1983. *Limnology*. Saunders College Publishing.

Widdel F. 1988. Microbiology and ecology of sulfate- and sulfur-reducing bacteria. In Zehnder A.J.B. (Editor) 1988 *Biology of Anaerobic Microorganisms* 469-585. Wiley.

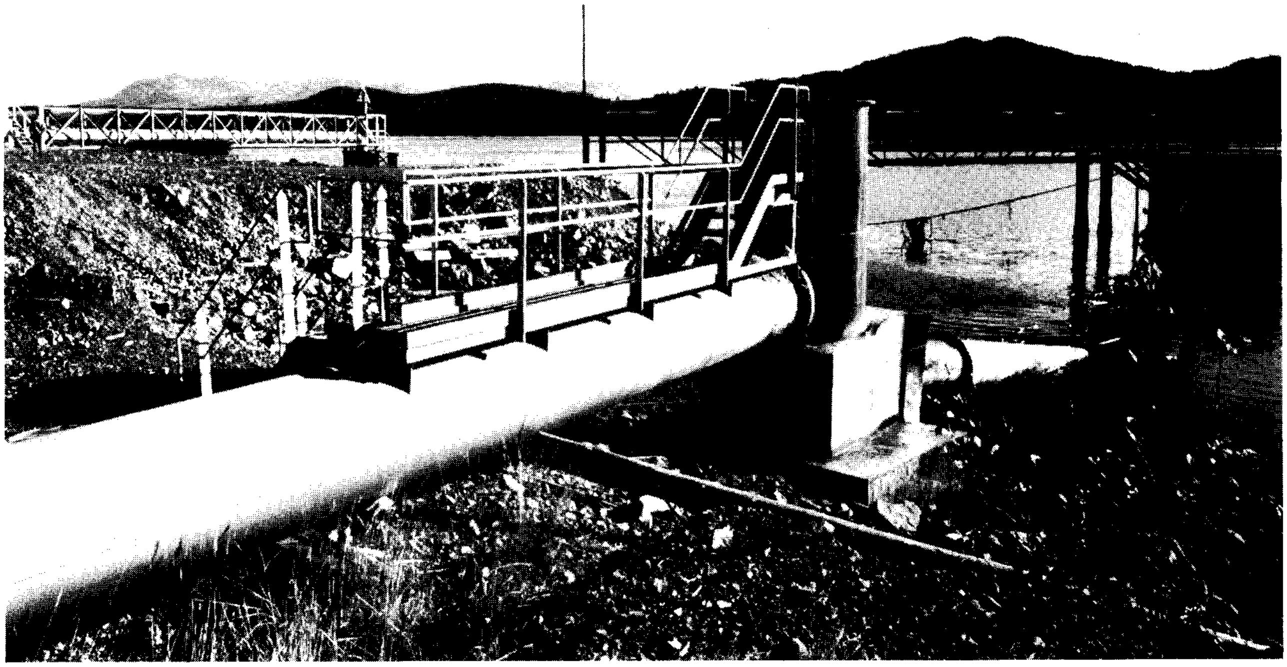
World Bank/International Finance Corporation. ND. Cayeli Bakir Isletmeleri Copper-Zinc Mining Project, Environmental Assessment Summary.

Appendix 1.

Submarine Tailings Outfalls at Island Copper Mine, Canada



Appendix 1.1 - The two STD outfalls at Island Copper Mine as seen from the sea. The outfall on the left is currently operational. The tailings line descends underwater and discharges to the de-aeration tank. This is accessed by a catwalk from the shore. The original outfall is to the right, and is now a standby. The tailings line is within a catwalk and discharges from above into the de-aeration tank. A band of intertidal biological growth shows up white around the lower part of both tanks.



Appendix 1.2 - The two STD outfalls at Island Copper Mine as seen from the land. The operational outfall is in the foreground and shows the tailings line descending underwater towards the de-aeration tank. The standby outfall is in the mid-ground, and the discharging tailings slurry can just be seen at the end of the pipe. The size scale is indicated by the man standing beside the standby outfall.